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CORRECTIONS AND INSERTIONS

Contributors to volume 40 have been invited to send corrections and insertions to be made in their paper, and the volume has been scanned with some care by the Editor. The following are such corrections and insertions as are deemed worthy of attention:

Plate 19, Varves at Squantum, figure 2 should be reversed

Page 346, line 10 from bottom, *for* "attended" *read* extended

" 350, line 15 from top, *after* "late Paleozoic time" *insert* (Figure 1)

" 392, footnote, *for* "Transactions" *read* Translation

" 412, line 3 from top, *for* "indicate" *read* indicates.

" 416, line 11 from top, *for* "Chamberlain" *read* Chamberlin

" 464, line 6 from top, *before* "Carbonaceous" *insert* from

" 484, last line, *for* "unpublished manuscripts," *read* Report of Investigations, number 19, 1929.

" 531, paragraph three, *change* last three sentences to read:

> Thus the Bryn Mawr gravel at Harrisburg has a present altitude of 520 feet; when the gravel was deposited its altitude was 70 (miles) times 3 (inches) or 18 feet, indicating a subsequent rise of approximately 500 feet. The present altitude of the Brandywine gravel, at the same place, is 430 feet. When this gravel was deposited its altitude was 40 feet, indicating a subsequent rise of 390 feet.

" 538, Table 1, column 3, ratio of Mono Lake NaCl *for* .063 *read* 0.63

" 546, plate 19, figure 2 is upside down

" 555, line 7, *for* "Formations in Timiskaming County, Quebec" *read* Keewatin of Lake Superior region

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 40, PP. 1-160, PLS. 1-6 MARCH 30, 1929

PROCEEDINGS OF THE FORTY-FIRST ANNUAL MEETING OF THE GEOLOGICAL SOCIETY OF AMERICA, HELD AT NEW YORK, NEW YORK, WEDNESDAY, THURSDAY, FRIDAY, AND SATURDAY, DECEMBER 26, 27, 28, AND 29, 1928.

CHARLES P. BERKEY, *Secretary*

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Session of Wednesday Afternoon, December 26

A joint session with Section E of the American Association for the Advancement of Science was held preliminary to the formal opening of the Forty-first Annual Meeting of the Geological Society of America. The meeting was called to order at 1 o'clock in the Duplex Assembly Room, School Service Building, American Museum of Natural History, New York City, by Frank Leverett, Vice-President of Section E.

The meeting was devoted entirely to the reading of scientific papers, chiefly by non-members of the Geological Society of America. Twenty-five titles were presented. Full account of the session, including titles and abstracts, may be found in the Proceedings of Section E, printed elsewhere in this number of the Bulletin.

Meetings of Wednesday Evening

Presidential address by Bailey Willis

The address of the retiring President, Bailey Willis, entitled "Continental genesis," was delivered before the combined societies in the Duplex Assembly Room, School Service Building, American Museum of Natural History, at 8 o'clock. The address is published elsewhere in this number of the Bulletin.

ANNUAL SMOKER

At the conclusion of the presidential address the members of the Geological Society of America, of Section E of the American Association for the Advancement of Science, and of the affiliated and associated societies and their guests, adjourned to the fourth floor of the Museum to participate in the complimentary smoker given by the local members of the Society. This function was largely attended and an opportunity was given for renewal of acquaintances and general social enjoyment.

SESSION OF THURSDAY MORNING, DECEMBER 27

The Forty-first Annual Meeting of the Geological Society of America was called to order in the Duplex Assembly Room, School Service Building, American Museum of Natural History, New York, New York, at 9.30 a. m., by President Willis.

REPORT OF THE COUNCIL

The report of the Council was presented by the Secretary, as follows:

To the Geological Society of America, in forty-first annual meeting assembled:

The regular annual meeting of the Council was held at Cleveland, Ohio, in connection with the Annual Meeting of the Society December 29-31, 1927. Special meetings of the Council also were held in New York City on April 14, 1928, and September 22, 1928.

The details of administration for the fortieth year of the existence of the Society are given in the following reports of the officers:

PRESIDENT'S REPORT

To the Council of the Geological Society of America:

The report of the President for the year ending November 30, 1928, is as follows:

In our Society the honorary position of President carries with it no administrative duties. Members who may wish to know what the Society has done during the year are referred to the report of the Secretary. He did it.

The list of the committees which have acted for the members as a body is appended and will show what each accomplished. We owe to them as

well as especially to the Secretary our appreciation for their efficient performance of their duties.

The function of our Society is to promote good fellowship. Good fellowship in personal relations was its original object, for it was founded at a time when the divisions in our ranks were serious. That situation was long since completely overcome, chiefly by the personal contacts brought about by the meetings of the Society and by the example of the great men who founded the organization. But good fellowship can go much further into cooperative research than is at present the practice. Geologic research is exceedingly diverse. One might compare the common stock of knowledge to a gnarled old trunk on which many kinds of fruit have been grafted. Each of us begins by climbing the trunk, but presently he starts out on a branch, picks the fruit it bears, and tastes no other. In fact, he too often specializes in diet until he can't eat any other.

So far as any individual is concerned this is perhaps not important, but for the growth of knowledge along sound developments it is, and it is a condition of which the Society may well take cognizance. I suggest that it would be well that the Society, or rather a committee acting for the members, should constitute a clearing-house, judiciously and tactfully to promote cooperative relations in research.

Apart from the gatherings that do so much for social relations and discussion our chief object is to publish the work of our members and of those whom they may introduce. We do not do it efficiently. The censorship and editorship are excellent, but publication is far too slow. The reason is that we depend on gratuitous service from colleagues who carry other administrative burdens and we thus add to the handicap which administration ever imposes on research. It is poor business from every point of view and should be overcome by reorganization on a paid basis.

Our colleagues of the Society of Economic Geologists have organized to publish an abstract journal, a desideratum long wanted by geologists in general. It may be hoped that we shall find the means to cooperate with them and to expand the scope of the work to include all branches of geology. Every geologist can contribute toward that end by abstracting his own paper and sending the abstract to the editor of their journal for consideration.

Our Society is affiliated with others of like interests in research, especially the Paleontologists, the Mineralogists, and the Economic Geologists. The Seismologists also belong to the group, though not now

affiliated. The Petroleum Geologists likewise have much in common with us. The tendency of specialized research and of geographic isolation is to further divide us and thus to lead to dispersion of energy as well as loss of prestige as a factor in the progress of knowledge. There is occasion and there is opportunity for closer organization, for which examples are not lacking, in order that geology shall take its rightful place among the sciences in advancing civilization and knowledge.

At the Cleveland meeting those who were present at the presentation of the Penrose medal listened to an eloquent appeal from the boldest explorer and most profound investigator American science has known in our day, if not since the beginning. He called to us as if from a mountain height to strike out and occupy the fields of research which he himself had penetrated and which he described as ours. You or I may respond as individuals, but that is not enough. Our Society should advance with a broad front, cooperating on every hand with fellow scientists to spread our research on every branch of investigation from the physics of a crystal to the orbits of the planets.

A considerable number of Fellows have given their time and thought to the business of the Society through its committees. The scope and personnel of the committees are indicated in the following list, as well as appointments made for special occasions:

1928 Committees and Special Appointments

Membership Committee: Nelson H. Darton (Chairman), Henry B. Kummel, William E. Wrather.

Committee on Foreign Correspondents: Waldemar Lindgren (Chairman), William B. Scott, Arthur P. Coleman, Whitman Cross.

Finance Committee: Edward B. Mathews (Chairman), Fred E. Wright, Joseph Stanley-Brown, R. A. F. Penrose, Jr.

Special Finance Committee: Edward B. Mathews (Chairman), Fred E. Wright, Joseph Stanley-Brown, R. A. F. Penrose, Jr., Waldemar Lindgren, Edward W. Berry.

Committee on Publication: Charles P. Berkey, Edward B. Mathews, Joseph Stanley-Brown, Nelson H. Darton, H. Foster Bain.

Committee on Exchanges: Charles Schuchert (Chairman), Edward W. Berry, Henry S. Washington.

Penrose Medal Committee on Award: Arthur Keith (Chairman), Frank D. Adams, David White, Whitman Cross, John C. Merriam, Arthur P. Coleman, Arthur L. Day.

Committee on Secretarial Adjustments: Charles P. Berkey (Chairman), Joseph Stanley-Brown, H. Foster Bain.

Program Committee: Charles P. Berkey (Chairman), R. J. Colony, R. S. Bassler, Frank R. Van Horn, George R. Mansfield, Edward Sampson.

Local Committee for the New York Meeting: Charles P. Berkey (Chairman), Chester A. Reeds, Albert O. Hayes, R. J. Colony, George F. Kunz, Ida H. Ogilvie.

During the year several important appointments have been made of delegates to scientific meetings and representatives of the Society at public functions and celebrations, as follows:

Inauguration of Matthew Lyle Spencer as President of the University of Washington: Delegates, Henry Landes, Charles E. Weaver.

Second International Conference on Bituminous Coal: Representatives, H. Foster Bain, David White, George H. Ashley.

Inauguration of Harvey Nathaniel Davis as President of Stevens Institute of Technology: Delegates, Charles P. Berkey and R. J. Colony.

The Joseph A. Holmes Safety Association: Representative, John J. Rutledge.

The Society of Economic Geologists: Delegate, H. Foster Bain.

Respectfully submitted,

BAILEY WILLIS,
President.

SECRETARY'S REPORT

To the Council of the Geological Society of America:

The Secretary's annual report for the year ending November 30, 1928, is as follows:

Meetings.—The proceedings of the annual meeting of the Society, held at Cleveland, Ohio, December 29-31, 1927, have been recorded in volume 39, pages 1-260 of the Bulletin. Those of the Cordilleran Section, pages 261-270 of the Bulletin; of Section E of the American Association for the Advancement of Science, pages 271-280; of the Paleontological Society, pages 281-312; of the Mineralogical Society, pages 313-320 of the same volume.

Membership.—During the last year the Society has lost by death one Correspondent—Emanuel Kayser—and seven Fellows—John Adams Bownocker, Thomas Chrowder Chamberlin, Bashford Dean, Joseph S. Diller, Edward V. d'Invilliers, Frank L. Nason, and William North Rice. The names of the thirty-one candidates for Fellowship elected at the Cleveland meeting have been added to the printed list. One name has been dropped from the list for non-payment of dues. The present

enrollment of the Society is 550. Fifteen candidates for Fellowship and three for Correspondentship are before the Society for election, and a number of applications are under consideration by the Council.

Distribution of the Bulletin.—During the past year there have been sent out to domestic subscribers 198 copies and to foreign subscribers 85 copies of the Bulletin, 34 going to new subscribers. This shows an increase in subscriptions over last year of 15 copies. Eight volumes have been distributed gratis, as follows: The Library of Congress; the Government Geological Surveys of the United States, Canada, and Mexico; the Bureau of Science, Manila, Philippine Islands; the Smithsonian Institution, Washington, D. C.; the Case Library, Cleveland, Ohio; the Columbia University Library, New York City. The present exchange list comprises 53 addresses.

The receipts of this office, including subscriptions to and sales of the Bulletin and separate brochures therefrom, are summarized as follows:

Detailed Financial Statement of the Secretary's Office

RECEIPTS

Regular subscriptions	$2,469.00
Irregular sales	1,702.35
Geological Magazine	29.20
Post and express refunds	70.53
Authors' separates and corrections	92.84
Exchange added to checks	.10
Circulars furnished to Paleontological Society	17.55
Paper stock sold to Judd and Detweiler	182.25
Total receipts from all sources	$4,563.82
Amount forwarded to Treasurer	$4,563.82

RECEIPTS FOR SPECIAL PURPOSES

On account extra expenses in connection with the 1928 program and preparations for the New York meeting, gift	$500.00

DISBURSEMENTS

On account of administration:	
Printing expenses, Cleveland meeting	$606.50
Printing for 1928	96.55
Clerical help for 1927	200.00
Clerical help for 1928	400.00
Postage	161.16
Telegrams and telephone calls	16.86
Addressograph plates and repairs to machine	10.99
Carfare	.50
Binding 4 volumes of the Bulletin	19.00
Total	$1,511.56

On account of Bulletin:

Office expenses:

Post and express charges	$164.77
Carfare	3.30
Notary fees	1.25
Printing	9.20
Supplies	4.85
Total	$183.37

Through the generosity of Dr. R. A. F. Penrose, Jr., a special fund of five hundred dollars has been available for additional support of the Secretary's office in connection with the program and extra work of the New York meeting of the Society. An accounting of the expenditure of this special fund will be included in the report for the fiscal year ending November 30, 1929.

The routine work of the Secretary's office has grown to such proportions in recent years that it is now a serious burden to the present incumbent, who has many other responsibilities. Except for the very efficient assistance of Mrs. Miriam F. Howells, who carries the responsibility of much of the routine, it could not have been done. The special support noted above was intended wholly to relieve some of this pressure, and has made continuation through the year possible.

The time has come, however, when it is quite necessary for the present Secretary to turn his responsibility over to other hands. A committee has had the matter under advisement for the past year but has not to this time fully solved the problem. It is somewhat involved with other matters that should be cleared up first. These are questions belonging chiefly to the Council. The steps taken, including that of incorporation, are calculated to improve the whole situation, and doubtless the secretarial problem can be cleared up during the coming year.

Respectfully submitted,

CHARLES P. BERKEY,
Secretary.

TREASURER'S REPORT

To the Council of the Geological Society of America:

The Treasurer herewith submits his report for the year ending November 30, 1928.

The membership of the Society on December 1, 1927, consisted of 417 Annual Members, 90 Life Members, and 21 Correspondents. Thirty-one new members qualified during the year, 2 of them commuting for life.

One Correspondent, 3 Life Members, and 4 Annual Members have died during the year and 1 was dropped for the non-payment of dues.

As the books close, the membership of the Society consists of 440 Annual Members, 90 Life Members, and 20 Correspondents, making a total of 550.

	Receivable Jan. 1, 1928	Collected to Nov. 30, 1928	Due Dec. 1, 1928
Fees of delinquents, 1925, 1926, 1927	$230.00	$120.00	$110.00
Fees for 1928	4,480.00	4,170.00	280.00
Initiation fees	310.00	310.00	
	5,020.00	4,600.00	
Adjustments	100.00*	290.00†	
	4,920.00	4,890.00	
Less 3 Life commutations	30.00		
	4,890.00		
*Written off for non-contributing members	20.00		
Written off for 2 delinquents dropped	80.00		
		100.00*	
†Received prior to 1928	10.00		
Present delinquencies	280.00		
		290.00	
RECEIPTS			
Cash on hand, December 1, 1927		$4,776.01	
Annual dues:			
1925 (1)	$10.00		
1926 (1)	10.00		
1927 (10)	100.00		
1928 (417)	4,170.00		
1929 (4)	40.00		
1930 (1)	10.00		
		4,340.00	
Initiation fees (31)		310.00	
Life commutations (3)		450.00	
Case Library for accessions		150.00	
Interest:			
On investments	2,120.00		
On Penrose Fund	100.00		
On bank balances	129.10		
		2,349.10	
Amount added to checks		.34	
Received from Secretary:			
Bulletin sales	4,171.35		
Geological Magazine	29.20		
Authors' separates	85.59		
Exchange on checks	.10		

*Two Shawinigan Water and Power Company.
†Two Southern Pacific Railway.

Refunds, etc.	$70.53		
Paleontological Society	17.55		
Miscellaneous	189.50		
		$4,563.82	
			$16,939.27

EXPENDITURES

Secretary's office:			
Administration	$1,511.56		
Bulletin	183.37		
Geological Magazine	29.34		
Allowance	1,000.00		
		$2,724.27	
Treasurer's office:			
Expenses	115.50		
Clerk	150.00		
		265.50	
Publication of Bulletin:			
Printing	3,472.12		
Engraving	1,134.91		
Paper	1,922.90		
Editing	515.00		
		7,044.93	
Mineralogical Society of America		117.00	
Cordilleran Section		120.57	
Purchase of rare volumes of Bulletin		57.50	
Investments:			
Four bonds	3,984.25*		
Interest on same	9.01		
		3,993.26	
Publicity		105.00	
Miscellaneous		23.43	
			$14,451.46
Balance in bank, November 30, 1928			2,487.81
			$16,939.27

The book value of the securities held by the Treasurer at the present time is $44,063.50.

Respectfully submitted,

EDWARD B. MATHEWS,
Treasurer.

EDITOR'S REPORT

To the Council of the Geological Society of America:

The following tables cover statistical data for the thirty-nine volumes thus far issued:

* Two Shawinigan Water and Power Company.

ANALYSIS OF COSTS OF PUBLICATION

Cost	Average, Vols. 1–35	Vol. 36	Vol. 37	Vol. 38
	Pp. 732, pls. 29	Pp. 727, pls. 10	Pp. 685, pls. 20	Pp. 881, pls. 21
Letter press	$1,895.32	$2,737.89	$2,852.45	$3495.67
Illustrations	436.82	528.90	414.56	848.08
Paper	404.10	411.96	502.76	670.74
Total	$2,736.24	$3,678.75	$3,769.77	$5014.49
Average per page	$3.74	$5.06	$5.45	$5.67

CLASSIFICATION OF SUBJECT-MATTER

Volume	Areal geology	Physical geology	Glacial geology	Physiographic geology	Petrographic geology	Stratigraphic geology	Paleontologic geology	Economic geology	Official matter	Memorials	Unclassified	Total
	Number of pages											
1	116	137	92	18	83	44	47	..	60	4	4	593+xii
2	56	110	60	111	52	168	47	9	55	1	7	662+xiv
3	56	41	44	41	32	158	104	..	61	15	1	541+xii
4	25	134	38	74	52	52	14	..	47	32	2	458+xii
5	138	135	70	54	28	51	107	..	71	14	9	665+xii
6	50	111	75	39	71	99	1	..	63	25	4	538+x
7	38	77	105	53	40	21	123	4	66	28	13	558+x
8	34	50	98	5	43	67	58	14	79	8	..	446+x
9	2	102	138	..	44	28	64	16	64	12	..	460+x
10	35	33	96	37	59	62	68	28	84	27	17	534+xiii
11	65	110	21	10	54	31	188	7	71	60	46	651+xii
12	199	39	55	53	24	98	5	5	70	2	..	538+xi
13	125	17	13	24	28	116	42	4	165	32	29	583+xii
14	48	47	48	59	183	118	22	1	80	14	1	609+xi
15	26	124	3	94	36	267	..	..	77	17	3	636+x
16	64	111	78	30	102	141	19	..	67	22	15	636+xiii
17	49	161	41	84	47	294	27	..	71	9	2	785+xiv
18	16	164	141	5	29	246	5	..	68	40	3	717+xii
19	106	108	29	66	30	155	32	..	56	15	20	617+x
20	43	54	35	29	37	45	303	8	60	3	132	749+xiv
21	72	234	75	48	85	70	106	1	111	11	10	823+xvi
22	23	54	28	28	23	403	74	..	63	49	1	747+xii
23	75	52	126	108	19	145	134	..	66	32	1	758+xvi
24	18	57	96	57	49	160	106	23	133	53	3	737+xviii
25	34	211	54	32	156	9	175	..	108	9	22	802+xviii
26	..	72	23	11	56	90	148	..	54	44	6	504+xxi
27	1	59	125	31	146	20	271	2	73	24	5	739+xviii
28	25	273	70	69	78	200	55	39	94	110	14	1005+xxii
29	3	107	62	15	127	169	64	..	73	57	21	679+xix
30	160	3	41	9	5	36	205	16	73	59	50	644+xiii
31	1	80	19	4	13	45	22	21	69	97	79	450+xviii
32	73	47	7	27	63	51	77	17	105	2	37	488+xviii
33	39	166	160	47	97	107	101	3	91	41	31	862+xxi
34	20	256	73	2	39	149	48	..	89	38	64	778+xx
35	44	72	17	83	70	140	269	..	76	46	79	896+xxii
36	26	112	27	59	108	103	77	1	74	116	4	707+xx
37	53	101	8	8	16	111	126	43	74	126	1	667+xviii
38	148	88	17	26	41	265	98	..	73	88	13	857+xxiv
39	25	209	160	185	35	111	228	..	94	129	19	1195+xxx

Respectfully submitted,

JOSEPH STANLEY-BROWN, *Editor.*

The foregoing report is respectfully submitted.

December 27, 1928.

THE COUNCIL.

ELECTION OF AUDITING COMMITTEE

The printed report of the Council was distributed to all members in attendance, and action was delayed on acceptance of the report until such time as an auditing committee could examine the accounts of the Treasurer and make report. An auditing committee was then named, consisting of Edward W. Berry (chairman), George F. Kay, and Lewis G. Westgate.

ELECTION OF OFFICERS, REPRESENTATIVES, CORRESPONDENTS, AND FELLOWS

The Secretary then read the results of the ballot for officers of the Society for the year 1929, and representatives on the National Research Council, and of the ballot for Correspondents and Fellows. The following were declared elected:

President:

HEINRICH RIES, Ithaca, New York

First Vice-President:

WILLIAM S. BAYLEY, Urbana, Illinois

Second Vice-President:

U. S. GRANT, Evanston, Illinois

Vice-President to represent the Paleontological Society:

ERMINE C. CASE, Ann Arbor, Michigan

Secretary:

CHARLES P. BERKEY, New York City

Treasurer:

EDWARD B. MATHEWS, Baltimore, Maryland

Editor:

JOSEPH STANLEY-BROWN, New York City

Councilors (1929-1931):

HERDMAN F. CLELAND, Williamstown, Massachusetts

ELWOOD S. MOORE, Toronto, Canada

Representatives on the National Research Council (July 1, 1929, to June 30, 1932):

KIRK BRYAN, Washington, D. C.

JOHN B. REESIDE, JR., Hyattsville, Maryland

CORRESPONDENTS

SIR JOHN SMITH FLETT, Director, Geological Survey of England and British Museum of Natural History, London, England.

PIERRE MARIE TERMIER, Professor of Mineralogy, National School of Mines, Paris, France.

FELLOWS

HORACE NOBLE CORYELL, B. A., M. A., Ph. D., Instructor in Geology and Paleontology, Columbia University, New York, New York.

GEORGE IRVING FINLAY, A. B., Ph. D., Associate Professor of Geology, New York University, New York, New York.

PHILIP GEOFFREY BRITTON GILBERT, B. Sc., A. M., Ph. D., Geologist, New Jersey Zinc Company, Austinville, Virginia.

JOSEPH LINCOLN GILLSON, B. S., M. A., M. S., Sc. D., Associate Professor of Mineralogy and Petrography, Massachusetts Institute of Technology, Cambridge, Massachusetts; Geologist, E. I. Dupont de Nemours Company, Wilmington, Delaware.

HAROLD WILLIAM HOOTS, B. S., Ph. D., Assistant Geologist, United States Geological Survey, California Institute of Technology, Pasadena, California.

JOHN TIPTON LONSDALE, B. A., M. S., Ph. D., Geologist, Bureau of Economic Geology, University of Texas, Austin, Texas.

ARTHUR LEONARD PARSONS, B. A., Associate Professor of Mineralogy, University of Toronto, Toronto, Canada.

ARTHUR M. PIPER, B. S., M. S., Assistant Geologist, United States Geological Survey, Washington, D. C.

EDWARD STAPLES COUSENS SMITH, S. B., A. M., Assistant Professor of Geology, Union College, Schenectady, New York.

ALLYN COATS SWINNERTON, A. B., A. M., Ph. D., Professor of Geology, Antioch College, Yellow Springs, Ohio.

DAVID GROSH THOMPSON, A. B., A. M., Geologist, Division of Ground Water, United States Geological Survey, Washington, D. C.

WILLIAM A. J. M. VAN WATERSCHOOT VAN DER GRACHT, LL. D., M. E., D. Sc., Vice-President, Marland Oil Company, Ponca City, Oklahoma.

ALFRED WANDKE, A. B., Ph. D., Mine Manager, Guanajuato Consolidated Mining and Milling Company, United Mines Company, Guanajuato, Mexico.

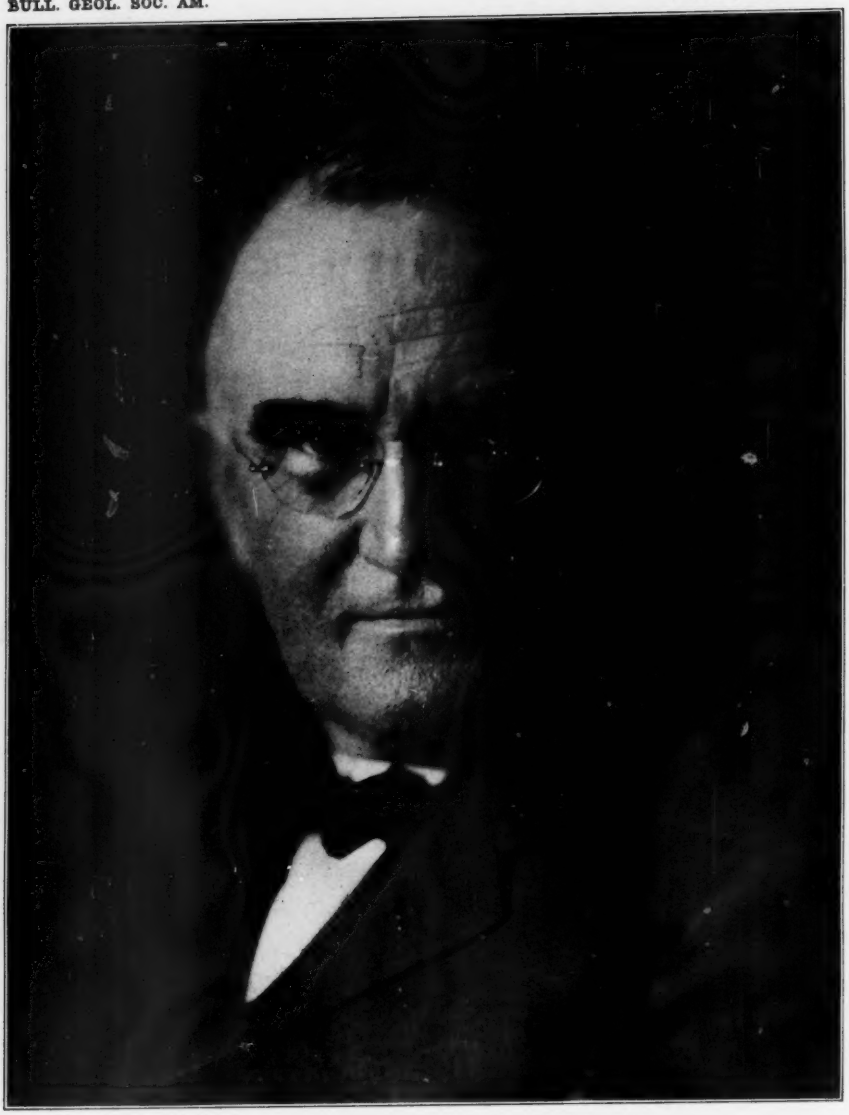
LUTHER HERMAN WHITE, A. B., Chief Geologist and Director, J. A. Hull Oil Company, Tulsa, Oklahoma.

ALFRED RUSSELL WHITMAN, B. S., M. S., Ph. D., Assistant Professor of Geology, University of California, at Los Angeles, California.

NECROLOGY

The Secretary announced the deaths of seven Fellows of the Society, and brief oral tributes were called for, as follows:

John Adams Bownocker, by C. R. Stauffer.
Thomas Chrowder Chamberlin, by Bailey Willis.



J. A. Bownocker

Frank L. Nason, by David H. Newland.
William North Rice, by Lewis G. Westgate.
Earle Sloan, by T. W. Vaughan.
Joseph S. Diller, by Arthur J. Collier.
Bashford Dean, by W. K. Gregory.

MEMORIALS

The following memorials are printed in the Proceedings of volume 40:

MEMORIAL OF JOHN ADAMS BOWNOCKER [1]

BY CLINTON R. STAUFFER

A stalwart, dignified bearing, with a warm friendly attitude toward all he met, made John A. Bownocker a person of distinction in any company. He liked people and they liked him, even from the first meeting. He had absolute honesty, unfailing loyalty, and a fearless attitude toward life, which caused him to face the future with hope and courage. His colleagues knew him as an industrious worker, devoted to the interests of the University and of the State; staunch in his upholding of proper standards of education, and of unusually good judgment in matters of educational policy. Students coming to him with problems were sure of a sympathetic audience, and many were the grateful youths who carried out from that conference a warmth of feeling for the man and an appreciation of his wise counsel.

John Adams Bownocker, born near Saint Paul, Fairfield County, Ohio, March 11, 1865, was a son of Michael and Eliza (Adams) Bownocker. He was reared on the farm and got his early education at the local schools. During his early experiences there came to him an insatiable desire to know things and he longed for more and better training. His determination to attend the State University was crystallized by hearing a lecture which Dr. Edward Orton chanced to give in his community. He worked with this in view and saved his earnings. He arrived in Columbus in the autumn of 1883 and entered the beginning class of the preparatory department, then a part of Ohio State University. His integrity, dependability, cheerful, buoyant disposition and fine sense of humor soon made him many friends among both students and faculty. In Horton Literary Society, of which he became a member, he was known as an orator and a successful debater. This training, together with his kindly, tactful nature, made him particularly suited to the duties which later fell to his lot.

[1] Manuscript received by the Secretary of the Society, December 27, 1928.

Throughout his student days John A. Bownocker lived at the South Dormitory, or "Little Dorm," where room rent was free and the student furnished his own supplies, did all of his own work, and kept his room in such order as he chose. He was a strong and robust young man, willing and able to work. His one great need was money to supplement the fund of $35 with which he started his subfreshman course. He found a job as driver of the milk wagon for the dairy maintained by the university, and this he kept throughout his preparatory and university courses. He was up and at his work by 4 o'clock in the morning. Although his day was long and one would not think his work conducive to personal cleanliness, he appeared at his classes freshly groomed and was rated one of the best-dressed men in the university. During this time he formed the friendship of Prof. Henry A. Weber, of the Department of Agricultural Chemistry. He was often invited to this home, where Mrs. Weber was like a mother to him. The influence which thus entered his life was a strong factor in the developing of sturdy manhood. With all his daily duties, he still had some time for social life, while idle moments at his room were spent with the violin—an instrument of which he never tired and which served him throughout his life.

Dr. Edward Orton was State Geologist and Professor of Geology at the university during John A. Bownocker's college days. The courses and the field trips under this inspiring teacher interested him so much that he decided to become a geologist. In 1889 he received the B. Sc. degree from the Ohio State University and quit his work at the university dairy. He had not only paid his entire college expenses, but had a fund of $125 saved toward the cost of his advanced course. After graduation he accepted the principalship of the high school at Martins Ferry, Ohio. This he held for three years, and thus built up his fund for further study. The years 1892-1894 were spent in the University of Chicago as a Fellow in Geology, where he studied under Drs. T. C. Chamberlin, J. P. Iddings, and R. D. Salisbury. The year 1894-1895 he spent as a graduate student at Yale University, and the following year he returned to Ohio State University as assistant to Dr. Orton in the Department of Geology. Two years later (1897) he received the degree of D. Sc. from his alma mater.

Dr. Bownocker remained at Ohio State University throughout the remainder of his life, passing through the various stages of advancement from Assistant in Geology, 1895-1898; Assistant Professor of Geology, 1898-1899; Associate Professor of Inorganic Geology and Curator of the Museum, 1899-1901; Professor of Geology and Curator of the Museum,

1901-1918; to the rank of Professor and Head of the Department of Geology, 1918-1928. During parts of his earlier career he served as assistant on the Ohio and New Jersey Geological Surveys, and in 1906 was appointed State Geologist of Ohio, which position he still held at the time of his death.

Much detailed work was planned and accomplished during his tenure as State Geologist. The results of this work were published in a series of twenty-five bulletins and several State maps. These publications deal with nearly every phase of geology and are particularly valuable in their dealings with the mineral resources of the State.

Dr. Bownocker early developed a liking for the oil and gas industry and devoted much of his time to the geology of the producing fields in the Appalachian region. His papers on the subject began to appear during the first years of the present century and he soon became an authority on the petroleum fields of Ohio. During this time he was often called into consultation on the problems presented by this industry in his State. Administration of the Survey and of his rapidly growing department in the university, however, made increasing demands on his time, and he gave less and less of it to these outside affairs. It was in the administrative field that Dr. Bownocker probably gave his greatest service. With his well laid plans, work ran smoothly and efficiently. Those who served under his guidance felt his hand but lightly, for he usually chose men who would do the task assigned. There never was the evidence of hurry and bluster so frequently found in the office of the chief, but his work was done on time, and the same regularity usually prevailed throughout the organization. In his classes Dr. Bownocker presented his subject clearly and concisely. He rounded out his course fully and nothing was left in doubt. Extra time and attention were cheerfully accorded to those who showed a willingness to learn, but he had little time or use for the shiftless.

His later years were largely concerned with the building up of the Orton Library of Geology, made possible by the generous gifts of General Edward Orton as a memorial to his distinguished father. The outstanding value of this collection of books is a tribute to Dr. Bownocker's success in administering the trust and to his ability in locating and in acquiring rare sets such as are possessed by few other American State universities. He gave his life in cheerful and devoted service to his native State and to the university of which he was so intimately a part.

On June 12, 1911, Dr. Bownocker married Anna K. Flint, of Menomonie, Wisconsin, and she survives him. Together they built up the

home on 15th Avenue, Columbus, in which he took so much pride. It was a joy to see the spruces and the fruit trees in his company, for one could feel the enthusiasm of the man who planted them.

Dr. Bownocker was a Fellow of the Geological Society of America, which he served as Councilor in 1923. He was a Fellow of the Ohio Academy of Science, which he served as vice-president in 1900 and again in 1903; an honorary member of the Natural Gas Association of America, and a member of Sigma Xi, honorary scientific society; also a member of Chi Phi fraternity and of the Faculty Club, which latter he served as president during the year 1927.

In the latter part of February, 1928, Dr. Bownocker underwent a serious operation, from which he only partially recovered. He was able to be at his office in Orton Hall part of the time, but he never resumed his teaching. During the late summer he grew steadily worse and died at his home on October 21, 1928.

Dr. George W. Rightmire, President of Ohio State University, paid him the following tribute:

"The death of Prof. John A. Bownocker has just been announced and the entire university community is in deep sorrow. He was a familiar figure on the university campus for thirty-three years, and was recognized for his devoted interest to university life and activities, for his belief in the place of the university in the State and the life of the people, for his staunch upholding of proper standards of education, and for his well considered, balanced judgment concerning all matters relating to the ongoing of the institution.

"He will always be remembered as a person not only of stalwart figure, but stalwart resolution and accomplishment. His characteristics were a strong blend of the sturdy and the refined, forming a character respected by all, whose influence in the great development of the institution can not be measured, but which all will agree was very great.

"The university community will make a fitting recognition in due time of its great grief and of its high estimate of his fine character, his good fellowship, his appreciation of the fine things of life, and of his large place in the university organization."

The Faculty Club of Ohio State University, on October 23, 1928, adopted the following resolution:

"A man who lived his life in the heart of his native Ohio and who gave it all to the services of his Alma Mater, the Ohio State University, John Adams Bownocker has been very peculiarly our own. His death is to many of us like a death in the very family. His services to the university and to the State remain with us, and will find of themselves their right assessment, but we, his colleagues, are thinking now only of the man himself.

"Here in especial, here in the Faculty Club, his presence is so real that one's every side glance expects to find him listening, with what a grave and

humorous appreciation, to what we say of him. And indeed what we may say seems incomplete without his rising among us, with the old precise elocution, with the old air that is in time for such a motion, to move that we do now adjourn. One fancies that for his last utterance, his *nunc dimittis*, and that his tired spirit stood erect and fearless to say it.

"The man we know, four-square, rough-hewn shaped, as if of the granite of his own geology, none of us was deceived by his apparent grimness. His was a straight and simple nature, able and unswerving, and absolutely loyal. Today the violins that he loved are silent in his house.

"And today the Ohio he loved takes him home to itself. And we, his old friends, find life a little more bare, a little farther-lighted, like the October day on the country graveyard down by Amanda. Peace be with him and our blessing upon him."

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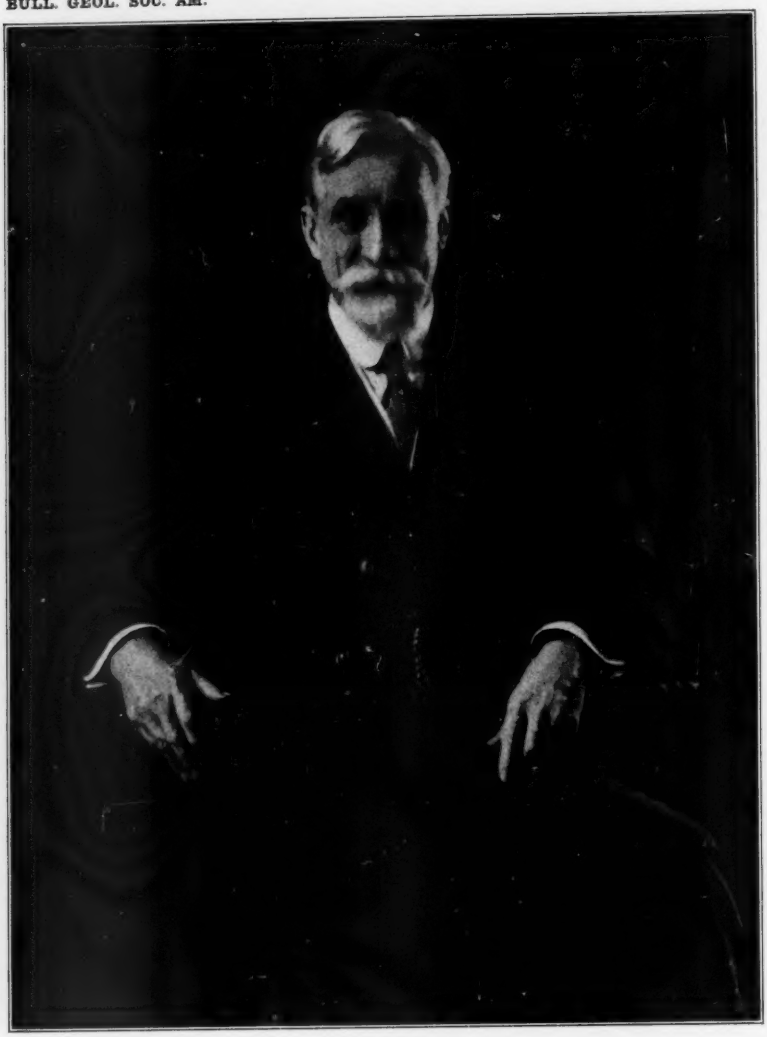

T. C. Chamberlin

MEMORIAL OF THOMAS CHROWDER CHAMBERLIN

BY BAILEY WILLIS

(1843-1928)

Aristotle, 322 B. C.; Copernicus, 1543 A. D.; Galileo, 1642; Newton, 1727; Laplace, 1827; Darwin, 1882; Chamberlin, 1928.

The names of great original thinkers are milestones along the path of exploration that penetrates the domain of the unknown. Chamberlin's is the latest. He has led into new realms where for a while others will survey and establish monuments, but whence also another, some great follower of his example, will again strike out in search of knowledge.

He was a great Master of Research. Few among living investigators have demonstrated equal capacity for inquiry. Very few indeed have sustained equal flights of constructive imagination yet kept in touch with the realities. None, in preparing for such flights, has more thoroughly utilized the resources of advancing science or more rigorously tested the records of altitudes attained.

Chamberlin fortunately lived during an epoch when the sciences were growing vigorously. He kept abreast of them. He was no follower. Neither was he an egotistical leader. Cooperating closely with competent companions, he advanced always with strong support. In the group of co-workers his was the mind that conceived the campaign against misconceptions. His also was the ingenuity which suggested critical tests of every new concept. That leadership was his because of his superior capacities: Initiative, independence, and insight. Yet the least experienced of his company received considerate attention and generous appreciation for any valid contribution.

Born at Mattoon, Illinois, September twenty-fifth, eighteen forty-three, Thomas Chrowder Chamberlin was eighty-five at his death, at Chicago, November fifteenth, nineteen twenty-eight. He was of large build, a vigorous, genial, generous personality.

From his father, who practised farming during six days and preached biblical philosophy every seventh day, Thomas appears to have inherited his intellectual capacity. He himself said: "I was brought up in theological philosophy, but it was not Calvinistic predestination. Individuality, personality, responsibility are so strongly ingrained in me that I cannot get rid of them." Evidently the father, like the son, was, within his own sphere, an independent, earnest, forceful thinker.

That he outgrew that restricted sphere of religious tradition, Chamberlin attributed largely to his environment as a boy. In a note on "little things" in his life he comments humorously on the fact that his birthplace was on the Shelbyville moraine, an intimation of his future interest

in glaciation. More seriously he describes the influence of all outdoors upon the growing farmer's boy.

"The most fascinating things of those days—to a boy of naturalistic bent—were the migrations of the birds, the spring migration in particular. The prairies were usually burnt over in the fall and so were often black and bleak during winter when not covered with snow, but as the spring advanced the grass began to make them grey and green, the buttercups and violets began to give them color, and then birds in uncounted flocks came from the south, fed upon them, and passed on. Blackness and bleakness gave place to color and life. No poor soul born in these days of plowed fields and wire fences ever see sights like those."

A limestone quarry, which he worked with his brothers for stone for the house that replaced an older log cabin, introduced the boy to rocks and also to "snails" and "snakes" ("Trenton" fossils). Having been taught Genesis in its most literal terms, he found in these vestiges of creation no questions except as to how the great snakes (orthoceratites) got down between the layers.

To the prairie "the skies came down equally on all sides" and the boy lived in the center. He watched the northern lights and looked for shootings stars. He grew alert, but not yet inquisitive or inquisitorial.

In strong contrast with the untrammeled outlook of his natural environment, was the limited scholasticism of his school training. Chamberlin's reaction was characteristic. When still a college boy, but taking his first examination for a teacher's certificate, he encountered the gymnastic problem: "If the third of six is three what would the fourth of twenty be?" The desired answer might have been an arithmetical calculation which would have shown that a fourth of twenty is seven and a half, but the young student at once refused the fallacy. He replied:

"The fourth of twenty is five under any and all circumstances and is not affected by any erroneous supposition that may be made in respect to a third of six."

Late in life he answered the question with a more explicit expression of his attitude toward false postulates, saying:

"If the third of six is three and if the whole universe were running on that crazy basis what might be the crazy proportion of the fourth of twenty?"

His conviction was profound that the Universe had not been created by a crazy creator, and his antagonism to "crazy" assumptions became intensified as the years passed. He had little patience with "denatured" theories. He held that

"The greatest genius is probably a genius for seeing the realities of things—all the essential realities of actual problems."

Chamberlin himself possessed that genius in very high degree and he developed it conscientiously, always endeavoring to make his analysis of the realities as complete as possible. He thus advanced, step by step, far beyond the range of less daring minds, and with some incurred the charge of being unduly speculative because they did not realize how clearly he saw the facts. But even though he himself strove to make a complete analysis, he welcomed suggestions cordially. Three weeks before he died he wrote a fellow geologist who had thought to strengthen a point in the Two Solar Families: "I hasten to acknowledge your contribution." He scorned pettiness and was incapable of appropriating another's thought unacknowledged.

Chamberlin was a teacher. His progress from the position of Principal of the Delavan High School (1866-68) to the "settee" of natural sciences at the State Normal School at Whitewater (1869-72), thence to the Professorship of Geology at Beloit (1873-82), to Columbian University (1885-87), and to Chicago University (1892-1919) was the natural evolution of a career of teaching for which he was peculiarly fitted. It was interrupted from 1887 to 1892 by his service as President of the University of Wisconsin. But the administrative office had little attraction for a mind that cared nothing for authority and was devoted to the acquisition and diffusion of knowledge. Once when tendered the directorship of the U. S. Geological Survey he responded that he had come to consider alternative views too habitually to act satisfactorily as an executive, who must often decide "yes" or "no" in doubtful cases.

The teacher and the investigator went hand in hand. The embryo of his thinking on geology is found in the suggestions of his environment as a boy. His intellectual force was inborn, but the work it was to do was determined by the puzzling and tantalizing, because unexplained, facts: "snails" and "snakes" in the rocks, the migration of birds, the aurora borealis, the stars, all outdoors. His reaction to the stimulus was characteristically demonstrated when he dismissed the formal classes of the Delavan High School on a throbbing spring day to "go out to see if we can find things in nature worth knowing and thinking about."

Entering into official relations as assistant geologist on the Wisconsin Survey (1873-76), Chamberlin was not given one of the preferred districts containing iron or lead, but was assigned to the economically barren southeastern quarter of the State. The rocks were the well known Paleozoic strata and they were deeply covered by glacial drift. The bald simplicity of the apparent problems might well have produced an intellectual chill, but Chamberlin's logical insight penetrated the superficial appearances and discovered the deeper question. Back of the Drift

phenomena was a mysterious cause of climatic change. To discover it became his main purpose, and the search conducted him through an investigation of the origin of the atmosphere to a theory of the evolution of the solar system.

Led by him with an intellectual leadership that has never been questioned, a group of able geologists has analyzed the drift sheets of North America, mapped their extent and detailed structure, and contributed a thorough understanding of the Pleistocene record. It is a great contribution. It demanded capacity for intimate and discriminating observation of differences where others saw sameness—for careful and alternative interpretation on the basis of process, stage, and environment, for balanced judgment and impartial testing of probabilities. It called for those qualities which Chamberlin already possessed to a high degree but which he was to train to even more difficult tasks.

As the complexity of the Glacial periods became more evident, the enigma of the cause grew more impressive. No satisfactory solution had been proposed, as appeared on testing the current theories by the accumulating facts. None was possible under the accepted doctrine of atmospheric evolution from the steaming envelope of a molten globe to the present life-giving air. The enigma deepened and broadened as the eager but patient student searched not only geology but all allied sciences for clues.

He gives Tyndall credit for the suggestion that led him to consider the relation between climatic conditions and the constitution of the atmosphere. The proportion of carbonic acid appeared to be a critical factor. The variables involved in its variation were found by Chamberlin to link geological, chemical, and biological processes in cycles of mutual reactions. The antiquity of recurrent climatic changes turned the investigation back from the Pleistocene to the pre-Cambrian glaciations, and thus to the origin of the atmosphere.

The inquirer could not pause there. The atmosphere of a molten earth indeed suggested tremendous possibilities, but they were not compatible with the facts of terrestrial history, so far as we can read it. The progress of knowledge had pushed a possible molten state of the earth even further back into vague traditional stages of creation.

Contrary to all that he had been taught, Chamberlin found himself obliged to consider alternative hypotheses that might be consistent with a less spectacular evolution, and he was forced to examine critically the very foundations of the geologic faith of that day.

He described his early work on theories of the genesis of the earth as resembling the exploration of an old mine to find what of value was left

in the outworked leads and to discover what promising veins might have been overlooked. The exploration occupied a number of years, demanded infinite patience, suspension of judgment, critical acumen, continuous self-instruction in the related branches of physics, chemistry, and celestial mechanics. Only a disciplined mind, trained absolutely to subordinate self-opinion to fact could have sustained the effort. If the example of Darwin was not consciously recognized, it was nevertheless paralleled.

Chamberlin recognized that terrestrial evolution is a *dynamic* process. Energy and force are vital, matter and environment simply important. This is the physicist's view, more rarely the geologist's. The dynamics of the globe are planetary dynamics. This is the astronomer's field, the geologist's only in the sense that "astronomy is the foreign department of geology."

Chamberlin's exploration thus reached into the realms of physics and astronomy. His powers of inductive reasoning did not fail him there, but he was not prepared to apply the methods of higher mathematics to research, as is commonly done in those sciences. He required associates to aid in testing hypotheses.

It does not appear that his environment developed favorable associations prior to his entrance into the faculty of Chicago University (1892). While at Columbian he was occupied with the more strictly geologic problems of Pleistocene classification. His associates, Gilbert, Dutton, and other fellow geologists, thought in the narrower field of terrestrial processes and he with them. He was one of a group of similar thinkers similarly equipped. At Chicago it was different. In that newly organized faculty were leaders in related sciences, and among the students there appeared from time to time competent aids eager to work with the master of research.

Two men stand out as Chamberlin's chief associates: Rollin D. Salisbury and Forest R. Moulton. In different fields each one contributed materially to his work. Salisbury, a student at Beloit, devoted himself loyally throughout his whole career to supporting Chamberlin. He worked with his chief in glacial geology, in the organization and conduct of the department of geology at Chicago, and in the editorial work on the Journal of Geology which they founded. He collaborated in the preparation of their comprehensive Manual of Geology, of which he wrote important sections. He was more than a helpful assistant in innumerable subsidiary tasks of administration, and he ranked high as a teacher. It was for Chamberlin a great good fortune to have drawn to himself a spirit so loyal, a collaborator so competent, a fellow teacher so superior as Salisbury.

Moulton brought to the cooperation with Chamberlin the resources of a mathematician and an astronomer. He was much younger than Chamberlin, and during their association developed from a young instructor to a mature scientist. In their research the method of multiple hypotheses controlled. Their objective was a tenable hypothesis of the origin of the planetary system. They examined all the hypotheses that occupied the field and devised many others, both comprehensive and subsidiary. Chamberlin's constructive mind grouped facts, originated explanations, suggested tests. He reasoned by "naturalistic logic." Moulton's analytical genius checked Chamberlin's concepts against the principles of celestial mechanics, and applied critical mathematical tests to the dynamical consequences. In their discussions each always maintained independence of judgment. When agreements were reached it was only on convincing proof.

Even so, agreement between Chamberlin and Moulton was not regarded by them as demonstration. An hypothesis was abandoned only when it was clearly inconsistent with known facts or laws. All hypotheses that withstood the tests of the realities were carried on as possible working material. Yet after twenty-five years of research only one hypothesis of planetary genesis, the Panetesimal, survived.

The gaseous group of genetic hypotheses represented by the theory of Laplace failed because the kinetic energy of gases would not permit the assembling of the actual planets by gravitation, as postulated, and the observed moments of momentum of revolution could not have been attained. The meteoritic hypotheses failed similarly to withstand Moulton's incisive studies of their dynamical implications.

Having failed to find a solution of their problem in the general concepts relating to the movements and attractions of stellar bodies, Chamberlin and Moulton turned their attention to the specific peculiarities of the solar system, in the hope of finding in them a suggestion of the conditions to which they owed their evolution. The orderly arrangement of the planets nearly in a common plane of orbits, the distribution of masses, which contrasts extraordinarily with the distribution of moments of momentum, the directions of rotation of the planets, and many minor peculiarities were critically studied. They suggested that two bodies had been concerned in the birth of the planets from the sun: the sun itself and a visiting star. This hint was developed constructively by Chamberlin and mathematically by Moulton, until the possibilities of a dynamical encounter had been traversed and that which seemed best to suit the actual facts of the solar system had been isolated from the general possibilities. This conception and demonstration belong entirely to

Chamberlin and Moulton; they constitute a great original contribution in the field of celestial mechanics.

Directing his attention specifically to the evolution of the earth, Chamberlin postulated the eruption of its mass from the sun as a result of the enormous expulsive activities of the sun, stimulated by the attraction of the passing star. This concept he has described as "the soul of the Planetesimal theory."

A mass of gas expelled from the pressure and temperature of the sun into the vacuum and cold of space presents dynamical problems which divide physicists. Would it assemble in response to its own gravitation and form a molten globe? or would it be dispersed by the kinetic energy of the gas? Chamberlin and Moulton approached the question as a sequel to their investigations of the Laplacian and related gaseous assemblages. They had demonstrated the inefficiency of gravitation and the effectiveness of kinetic dispersion. They were forced to recognize that the mass would become a swarm of minute solid bodies which would swing into orbits about the sun and would thus become "planetesimals." The real problem was to account for the fact that the planetesimals had assembled, that each swarm had become a planet.

The problem is not one which yields to mathematical analysis unless it be stripped of inherent complexities and simplified to suit an imaginary case. Chamberlin analyzed it logically. He grasped the complexity of cyclonic motion in the sun, the compressive action of the tidal effect, the dominance of the expulsive force, the drag effect upon the bolt, and the consequent resemblance of the mass to a rolling cloud. He reasoned the transformation of the billowing bolt into the orbital swarm, in consequence of the attraction of the passing star, the formation of a heavy core, and the gradual growth of the earth by the infall of planetesimals.

He first published these views in 1903-04 in reports to the Carnegie Institution of Washington on research in Fundamental Problems of Geology. He embodied them in more popular form in the Origin of the Earth, 1916. It was characteristic that to the end of his life he continued to pursue studies designed to test, modify, or perfect theories of the origin of the earth, including the Planetesimal. In 1926 he said concerning the latter:

> **"For twenty-five years I have tested every hypothesis of the genesis of the earth of which I could learn or which I could conceive. One and one only has withstood every critical test. Do you think I am justified in thinking it probably true?"**

In this attitude of mind he took up the review of his book, the Origin of the Earth, when it was to go to its fifth printing. The year was 1925;

he was eighty-two. With the wisdom of a veteran but with the courage of youth, he critically revised his earlier postulates—not to prove but to test them—and he came upon "a lion in the path." He had met lions before, such as the doctrine that the rotation of planets, if they were formed from solid accretions, should be backward instead of forward. For a long time that lion had barred the way from the field of gaseous origins to that of the planetesimals, but he had been shown to present a false front. Was this new lion more formidable?

The difficulty lay in the fact that the rotation of a cyclonic bolt must be around the axis of the bolt as it left the sun and would therefore be directed almost at right angles (67½ degrees) to the actual direction of rotation of the earth. Here was a dynamic contradiction of crucial significance, but, as Chamberlin said: "There was nothing to do but to go right at it." A shift of the axis of rotation was indicated. To a mind seeking catastrophic effects some violent accident might have been suggested, but neither the experience of the student nor the mechanics of the planetary system was consistent with such an assumption. The rotation of the earth had long been attributed to innumerable minute impulses. Similar minute but unsymmetrical impulses, due to the infalling planetesimals, and the eccentricity of density which is apparent in the full-grown earth might have caused a creeping of the axis of rotation during the growth of the globe. The suggestion was put to the test of mathematical study and found sound. Thus the lion was overcome.

This illustrates one of the lessons to be learned from Chamberlin's researches; namely, the value attaching to small effects recurring persistently during the ages. His capacity to detect causes of this nature grew out of the constant effort to keep in touch with the realities, all the realities.

Chamberlin's great contributions to science relate to the two extreme stages of the evolution of the earth: the formation of the planet and the subsequent history of its atmosphere. His research also traversed all intermediate phases of terrestrial history, and he cast a long look ahead. He hopefully forecast the evolution of man to higher and higher possibilities, without limitation of time or intellectual development. He himself set the example, advancing far—and beckoning.

The following is a summary of important events in connection with Professor Chamberlin's career:

Place and Date of Birth: Mattoon, Ill., September 25, 1843.

Occupation: Professor (Emeritus) of Geology, University of Chicago. Research Associate, Carnegie Institution of Washington.

Education and Degrees: A. B., Beloit Coll., 1866, A. M., 1869; graduate, science, U. of Mich., 1868-9; Ph.D., U. of Mich. and Wis. 1882; L.L.D., U. of Mich., Beloit Coll., and Columbian Univ., 1887, Univ. of Wis., 1904, Toronto Univ., 1913; Sc.D., Univ. of Ill., 1905, Univ. of Wis., 1920.

Positions: Prin. High Sch. at Delavan, Wis., 1866-68; Prof. Natural Science, State Normal School, Whitewater, Wis., 1869-72; Prof. Geology, Beloit, 1873-82; Columbian, 1885-87; Pres. U. of Wis., 1887-92; Prof. and Head Dept. of Geology and Dir. Walker Mus., U. of Chicago, 1892-1919; Emeritus Prof. Geology, U. of Chicago, Oct. 1, 1919—. Asst. State Geologist, Wis., 1873-6, Chief Geologist, 1876-82; U. S. Geologist in Charge of Glacial Div., 1882-1907; Investigator Fundamental Problems of Geology, Carnegie Institution, 1902-1909; Research Associate, same instn. since 1909.

Temporary or minor positions, prizes, medals, etc.: Geologist, Peary Relief Expedition, 1894; Consulting Geologist Wis. Geol. Survey; Commissioner Ill. Geol. Survey; Consulting Geologist, U. S. Geol. Survey; Mem. Commission for Oriental Edul. Investigation, 1909; Medal, Paris Expos. 1878, 1893; Helen Culver medal, Chicago Geog. Soc., 1910; Hayden mem. medal, Phila. Acad., 1920; Penrose medal, Soc. Econ. Geologists, 1924.

Membership in educational societies and offices with dates: Mem. Wis. Acad. Science, Arts and Letters (Pres. 1885-86); Geol. Soc. Amer. (Pres. 1895); Chicago Acad. Sci. (Pres. 1897-1915); Ill. Acad. Sci. (Pres. 1907); Amer. Assn. Adv. Sci. (Pres. 1908-9); Nat. Acad. Sci., Amer. Acad. Arts and Sci. of Boston; Geol. Soc. of Washington; Philosophical Soc. of Washington; Amer. Phil. Soc. of Philadelphia; Cor. Mem. N. Y. Acad., Acad. Nat. Sci. of Phila., Brit. Assn. for Adv. Sci., Geol. Soc. of Edinburg, Geol. Soc. of London, Geol. Soc. of Sweden, Geol. Soc. of Belgium.

Marriage and children: Married Alma Isabel Wilson, 1867 (deceased). One son, Rollin Thomas Chamberlin.

Chief Publications: Geology of Wisconsin; Treatise on Geology (with R. D. Salisbury), 1906; The Origin of the Earth, 1916. Numerous scientific and educational articles. Editor of The Journal of Geology.

Public offices, commissions, or positions of honor or trust:

On Wisconsin Geological Survey, 1873-82, first Assistant, later Director.
Special Commission to study the state of scientific education in China, 1908-9.
Trustee Beloit College.
Commissioner, Illinois Geological Survey, until 1919.
Consulting Geologist, U. S. Geological Survey, 1908.
Research Associate, Carnegie Institution of Washington.

Honors or decorations conferred:

Medal for geological publications, Paris Exposition of 1878.
Medal for geological publications, Paris Exposition of 1893.
Helen Culver medal of the Geographic Society of Chicago.

Bust of Thomas Chrowder Chamberlin presented to the University of Chicago, February 7, 1903, "in recognition of the eminent services of Professor Chamberlin to the science of geology."

Portrait of Professor Chamberlin presented to the University of Chicago on June 11, 1918.

Hayden Medal awarded by the Academy of Natural Sciences of Philadelphia, for distinguished work in Geology, 1920.

Penrose Medal, Society of Economic Geologists, 1924.

Penrose Medal, Geological Society of America, 1927.

Membership in technical, scientific, or professional societies:

Wisconsin Academy of Science, Arts, and Letters (President, 1885-87).
Geological Society of America (President, 1895).
Chicago Academy of Science (President for 18 years, 1897-1915).
Illinois Academy of Science (President, 1907).
American Association for the Advancement of Science (President, 1908-9).
National Academy of Sciences.
American Academy of Arts and Sciences, Boston.
Geological Society of Washington.
Philosophical Society of Washington.
American Philosophical Society, Philadelphia.
Correspondent of the Academy of Natural Sciences of Philadelphia.
Corresponding Member, British Association for the Advancement of Science.
Corresponding Member, Geological Society of Edinburgh.
Corresponding Member, Geological Society of London.
Corresponding Member, Geological Society of Sweden.
Corresponding Member, Geological Society of Belgium.
Corresponding Member, New York Academy of Science.
Sigma Xi.
Phi Beta Kappa.

Professional or Business Record:

1866-68, Principal Delavan High School.
1868-72, Professor of Natural Science, State Normal School, Whitewater, Wis.
1873-76, Professor of Geology, Beloit College.
1873-76, Assistant Geologist, Wisconsin Geological Survey.
1876-82, Chief Geologist, Wisconsin Geological Survey.
1878, Made a study of glaciers in Switzerland.
1882-86, Geologist, U. S. Geological Survey, Glacial Division.
1882-1908, Made a study of the glacial formations of America, under the U. S. Geological Survey.
1885-87, Professor of Geology, Columbian University.
1887-92, President University of Wisconsin.
1892-1919, Head Department of Geology, University of Chicago.
1892—, Senior Editor, Journal of Geology.
1894, Geologist to Peary Relief Expedition—made a study of glaciers in Greenland.
Contributed chapters on North American Glaciation to Geikie's "Great Ice Age."
1902-9, Investigator, Fundamental Problems of Geology, Carnegie Institution of Washington.
Consulting Geologist, Wisconsin Geological Survey.
1908—, Consulting Geologist, U. S. Geological Survey.
1909—, Research Associate, Carnegie Institution of Washington.

1909. Made a study of fundamental principles of geology, especially the study of the old hypotheses of the origin of the earth and the solar system, destructive criticism of these (in connection with F. R. Moulton) and their final rejection, and the development of an entirely new hypothesis now known as the Planetesimal Hypothesis. This view has been widely, though as yet not universally, accepted. It is perhaps Dr. Chamberlin's greatest contribution to science.

Developed a radically new view of the history of the atmosphere (from a key derived from G. Johnstone Stoney).

Made a study of tidal problems.

Carried on diastrophic studies, basing the great epochs of earth history on changes in the body of the earth.

1919. Professor Emeritus, Department of Geology, University of Chicago.

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4. Some evidences bearing upon the upheaval of the quartzites of Sauk and Columbia counties. Transactions of the Wisconsin Academy of Science, Arts, and Letters, volume II, 1873-74, pages 129-32.
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16. Annual Report of Progress and Results of the Wisconsin Geological Survey for 1878. State Printer, Madison, Wisconsin, 1879, 51 pages.
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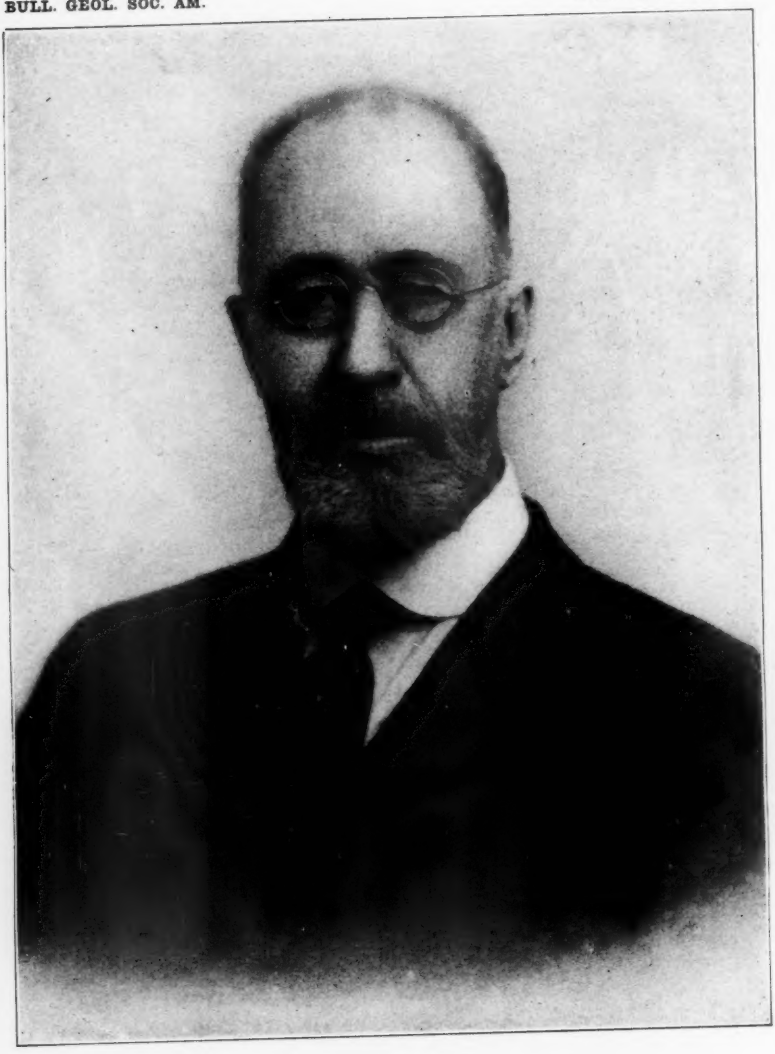

Frank Lewis Nason.

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MEMORIAL OF FRANK LEWIS NASON [1]

BY D. H. NEWLAND

By the death of Frank Lewis Nason the Geological Society of America lost one of the few remaining fellows of the original band of 98 who par-

[1] Manuscript received by the Secretary of the Society January 16, 1929.

ticipated in its organization. His membership dated back nearly 40 years, to the initial meeting at Ithaca, in December, 1888. At that time he was assistant on the Geological Survey of New Jersey. In the following year he contributed a paper on the "Watchung region of northern New Jersey and its traps," to the New York meeting of the Society. In 1890 he became connected with the Missouri Geological Survey, serving with it for two years, after which he withdrew from organized survey work and for the remainder of his life practiced as consulting geologist and field expert in ore exploration.

Nason was one of the pioneer economic geologists who helped to establish the new profession in public confidence when the possibilities of its services to industry were not so broadly recognized as within the last generation or two. There were few who ventured on that calling a generation ago independent of at least an incidental attachment to governmental or academic institutions for employment during part of the time. Nason, with his facile pen, found a means of capitalizing his experiences in the mining camps and newly settled agricultural regions of the West by the writing of novels, of which three were brought out by well known publishers in the years 1902-1905.

Of his early life few details have come to hand beyond those found in current biographies. He was of retiring disposition, not given much to personal confidences. He was of New England lineage, of the adventurous stock that helped to explore and settle the Mid-West, and was born at New London, Wisconsin, May 12, 1856. His father, Lewis Clark, and his mother, Maria (Stickles) Nason, lived on a farm. The death of the father, when Nason was a boy of 7, resulted in the breaking up of the home, and the widow with three children removed to Vermont, where the youth soon was able to contribute to the common support by working on a farm and in a machine shop. Attendance in public schools, as occasion afforded, qualified him at 22 for entrance at Amherst College, from which he was graduated in 1882 with the degree of A. B. It may well be assumed that his interest in geological study was then initiated or received an enduring stamp, under the instruction of Prof. B. K. Emerson, to whom so many fellows of this Society, past and present, have owed a similar debt. On leaving Amherst, however, Nason did not seek immediately further advancement in the science, but took up theological studies and spent one term at Yale Divinity School. He then joined the faculty of the Rensselaer Polytechnic School as instructor of mathematics, where, in addition to his class-room work, he participated in the curricular courses in chemistry, mineralogy, and

metallurgy. In 1888 he received and accepted an appointment on the Geological Survey of New Jersey, then under the directorship of Dr. George H. Cook. It was at this time probably that he first became acquainted in the field with the iron and zinc ores of the Precambrian formations, in which ever afterward he was deeply interested and to the literature of which he contributed many papers. In the reports of the New Jersey Survey issued between 1888 and 1890 are included contributions by Nason on the Triassic sandstones and traps, the white limestones which contain the Franklin Furnace zinc-iron-manganese ores, and of the Archean or Precambrian gneisses. The stratigraphic position of the white limestone long had been a fruitful source of speculation among geologists, attaining a classic standing in the literature of American geology, and the controversy, it may be remarked, was not definitely laid until some time after Nason's investigations, with the detailed mapping and petrographic studies by Wolff and Brooks.

On the death of Dr. Cooke, in 1889, John C. Smock became director of the New Jersey Survey, and Nason took service with the Missouri organization, for which he prepared an extensive report on the iron ores of that State. The field studies and compilation of the report required most of his attention for the next two years. He cooperated with Winslow and Haworth in the mapping and description of the Iron Mountain geological sheet, wherein some of the larger iron ore accumulations of Missouri are found. In 1893 he was in New York State and was engaged in special field investigations for James Hall, the outcome of which are the papers on the economic geology of Albany and Ulster counties included in the annual reports of the State Museum.

With this he terminated formal relationship with survey organizations and thereafter maintained an active practice with various industrial interests, chiefly iron and zinc enterprises in the Appalachian region. He varied such work, however, by occasional excursions into the western mining camps and oil fields and for a short time was manager of a Colorado mine. For many years he was mining geologist for the well known firm of Witherbee, Sherman & Company, whose extensive magnetite properties are in the Adirondacks of New York State.

He also acted in that capacity for the New Jersey Zinc Co., Basic Iron Ore Co., and Ringwood Furnace Co., and at different times was in the employ of the United States Steel Corporation, Virginia-Carolina Chemical Co., and the Standard Oil Co.

Besides his fellowship in the Geological Society of America, Nason held membership in the American Institute of Mining Engineers, Min-

ing and Metallurgical Society of America, and the American Association for the Advancement of Science.

In 1885 he married Thalia Abigail Potter, of West Haven, Connecticut, who died in 1906. They had two children, Stanley Lewis, who is a practicing mining engineer, and Alexia Painter, deceased. He married Madeleine Reynolds in 1909, who survives.

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MEMORIAL OF WILLIAM NORTH RICE [1]

BY LEWIS G. WESTGATE

William North Rice died on November 13, 1928, at the home of his son, Prof. Edward L. Rice, in Delaware, Ohio, eight days before his eighty-third birthday. Two days before, on Sunday, he had attended church service, taken his usual walk, and was in excellent spirits.

Professor Rice was a descendant, in the eighth generation, of Edmund Rice, who was born in England about 1594 and who settled in Sudbury, Massachusetts, in 1639. Nathan Rice, his great-grandfather, was a soldier in the Revolutionary War. His father, William Rice, a leader in New England Methodism, retired, on account of ill health, from the active ministry in 1857 and settled in Springfield, Massachusetts. In 1861 William Rice was elected librarian by the City Library Association of Springfield. This position he held till his death, in 1897, the library during that time growing to over 99,000 volumes and being transferred to a building especially constructed for it, now known as the William Rice Building. His mother was Caroline Laura North, daughter of William North, of Lowell, Massachusetts, a woman in every way worthy of her distinguished husband. Into this home of Christian culture and scholarly and literary interests William North Rice was born on November 21, 1845, while the father, still in the active ministry, was living at Marblehead, Massachusetts. After 1857 his home was in

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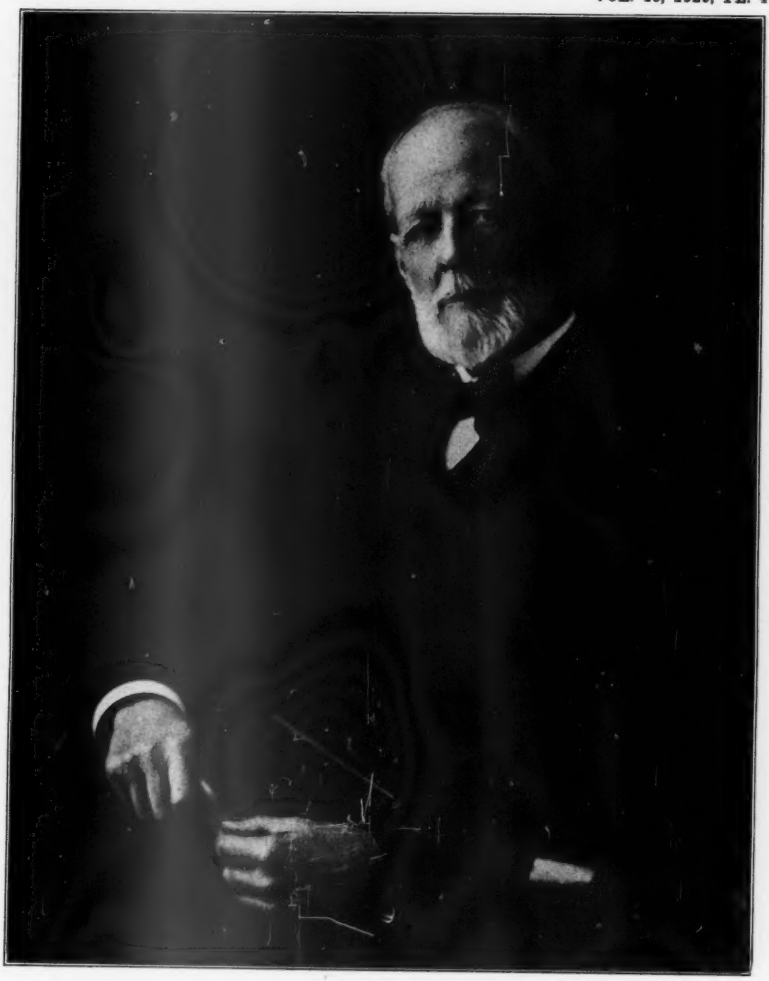

Wm. Morris Davis

Springfield. His college preparation was received chiefly in the Springfield High School. He entered Wesleyan University and later was graduated, the youngest member and the valedictorian of the class of 1865. He took the regular classical course, which at that time was almost completely prescribed; the only latitude allowed was a choice in junior year between Hebrew on the one hand and mechanics and French on the other

It is not clear why, in this environment, young Rice turned to science. His father was absolutely not interested in science. His mother was a fair botanist. Oliver Marcy, later Professor of Geology at Northwestern University, who was teaching science at Wilbraham Academy, near Springfield, knew Rice as a boy and helped him in the collection and identification of specimens. There was little inspiration to science in college, although John M. Van Vleck, who had just started on his long career as Professor of Mathematics and Astronomy, was his friend and was always regarded by Rice as the greatest teacher he had ever known. But, whatever the influence, to science he did turn, and, after two years of graduate work in Sheffield Scientific School of Yale University, he received the degree of doctor of philosophy in 1867, the first in geology given at Yale. (The first Ph. D. degrees in any subject at Yale were conferred in 1861.) For James D. Dana, as his teacher, as scholar, and as man, he had always the greatest reverence.

Immediately on leaving Yale he was appointed Professor of Geology and Natural History in Wesleyan, and after a year of study in Germany he commenced what proved to be a lifetime of service at his alma mater. In 1884 the work which he had been carrying was divided, and he continued as professor of geology until 1918, when he retired as emeritus professor of geology.

Professor Rice was first and always a teacher. Other monuments may be erected in his honor, but his chief monument will be the affectionate memory of the students who for fifty years sat under his teaching. Always accurate and careful, he insisted on these qualities in his students. Students could not, and rarely tried to, "get by," to use the modern vernacular. "We do not know, Professor," ventured "Duke" on one occasion, in answer to a not very difficult question. "Some of us do," was the quiet reply, and "Duke" did not try that lead again. Even college students enjoyed and respected the working of a mind which was a master of its own processes and materials. And there was always evident the intense love of truth and the enthusiasm for science that was so characteristic of the man.

Nor was Professor Rice's influence in educational matters confined to the class-room. At Wesleyan, perhaps more than in most colleges, the faculty determines general college policies; and in this work and in the work of administration Professor Rice's insight and balanced judgment have been of inestimable advantage to the college. Between 1870 and 1920 the three outstanding faculty leaders at Wesleyan were Van Vleck, Winchester, and Rice. Each was a great teacher and each exerted a large influence in the development of the college. They were largely responsible for the revolution of 1873, which did away with the old, rigid curriculum, introduced the elective system, advanced courses and the laboratory method, and made Wesleyan one of the leading smaller New England colleges, especially in science; and no one of the three was more responsible for this change and for guiding the subsequent educational evolution of Wesleyan than Professor Rice, though he would doubtless have put Van Vleck first. For ten years he was secretary of the faculty and for three periods acting president.

Professor Rice was an ordained minister of the Methodist Church and, while he never held a regular pastoral charge, was an occasional and effective preacher through life. His sermons were models of clear thinking, and his own deep sense of spiritual realities made a profound impression on his hearers. This double interest in religion and in teaching led him naturally into what is perhaps the most outstanding activity of his life, his study of and writings on the relations of science and religion. In the early seventies he had accepted the evolution theory—"Origin of Species" was a new book in 1865—and during the following years at Wesleyan, both in his college classes and in his Sunday afternoon Bible class, he was ever intent on helping the student to meet and accept the new scientific knowledge without loss of religious faith. Wesleyan students in those days who came under his influence were not troubled by evolution or Old Testament criticism. Out of this work came his best known and most important book, "Christian Faith in an Age of Science." There were Fundamentalists, even in those days, and when it was necessary to meet them outside college walls Professor Rice, who was a brilliant debater, never came off second best. A recent clash with John Roach Straton gave him especial joy, and when Straton began to quote Price's "The New Geology" (which he had recently reviewed and to which he commonly referred as "a pernicious book") his comment was, "Now hath the Lord delivered him into my hands." He used to say of himself, "I must be orthodox, for have I not for years been chairman of the Committee of the New York

East Conference of the Methodist Church, which has to pass on the orthodoxy of candidates for the Methodist ministry!"

Professor Rice's geological field-work, though it includes a report on the "Geology of Bermuda," was mostly done on the geology of Connecticut. He was asked to revise Dana's "Text-book of Geology" for the fifth edition. From 1903-1916 he was Superintendent of the Connecticut State Geological and Natural History Survey and gave a good share of his time to its work. In addition to planning its work and seeing the various Survey bulletins through the press, he wrote (with H. E. Gregory) "Manual of the Geology of Connecticut." For the same Survey two years ago he wrote (with W. G. Foye) "Guide to the Geology of Middletown." Professor Rice's knowledge of botany, zoology, and geology was wide and accurate. If his original production in geology is less than that of some of his geological contemporaries, it should be remembered that during the first sixteen years at Wesleyan he taught botany and zoology as well as geology, and that more and more in later years his interest was growing in the relations of science and religion. He considered that it was in this field that he had done his best and most useful work. He often said that he "would have done more if he hadn't tried to do so much"; and another might add, "and to do it so well."

Professor Rice has been a member of the Geological Society since 1890 and a nearly constant attendant on its winter meetings. In 1911 he was Vice-President. No one who was present will forget his moving address at the dinner at Ann Arbor, when H. E. Gregory as toastmaster called on him to answer the anti-evolutionists who were "hacking at our family tree." It was the next year, at Washington, that Professor Rice was presented by the Council, on behalf of the Society, with an engrossed and illuminated testimonial (See Bulletin, volume 35, page 117). He afterwards said: "When I consider how little geological work I have done, I am surprised and grateful for the recognition I have received from the Geological Society of America." That recognition was not only of his geological knowledge and work, but of his outstanding qualities as a man.

No account of Professor Rice can be at all satisfactory that does not put first the man, his mental and spiritual traits, rather than the work done; and yet how hard it is to do this adequately. He was small of stature and slight of build; and, while not at home in rough outdoor exercise, could outwalk most of his students. Perhaps one's first impression of him might be one of seriousness and logical perfection of mental processes. He spoke when he had something to say and, while

he enjoyed a joke as well as any, did not easily make small talk. He had the patience and conscience to make sure of his facts; few caught him napping here; and he had a mind fundamentally orderly and logical. Home training, education, and inclination made him a wide and thorough reader, especially in history and the best English prose and poetry, though he was not interested in technical philosophy. His favorite poets were Tennyson and Whittier, and one of his published essays was "Tennyson the Poet of Science." Perhaps it was his classical training that gave him his mastery of the niceties of the English language. He read his New Testament in the original Greek throughout life.

Keenness of intellect in Professor Rice was balanced by the depth and intensity of his ethical and religious life. He was a fair man, carrying over into every field of his thought the scientific attitude of mind. Everything was seen against a background of moral and religious values and took meaning from that background. His love of beauty in nature was profound, whether on walking tours in the Alps or along the shores and in the woods and fields of New England. This last fall, in central Ohio, he was out almost every afternoon, and his joy in the colors of autumn foliage and sunset sky was intense. And to him this world of nature was always God's world.

His interest in community educational and religious matters was constant. For some time he was president of the Middletown School Board. In recent years he has been a member of the Council of the Connecticut Federation of Churches, twice its president and for a long time its secretary. He was on the board of trustees of the West China Union University (Cheng-tu) and intensely interested in its work. He has always been interested in temperance, and on that ground, among others, was an ardent Hoover man during this last election. When he finally decided not to attempt to go back to Middletown to vote, he made partial amends by sending liberal contributions to the Connecticut State and local Republican committees and to the Anti-Saloon League.

Professor Rice was a member of the American Society of Naturalists (President in 1891), of the Geological Society of America (Vice-President, 1911), and of the American Association for the Advancement of Science (Vice-President and Chairman of Section E, 1905-1906).

In 1870 Professor Rice married Elizabeth W. Crowell, daughter of a Methodist minister, a woman of unusual intellectual and social qualities, and their long life together was ideally happy. She died in 1916. The surviving son, Edward L. Rice, is Professor of Zoology in Ohio Wesleyan University.

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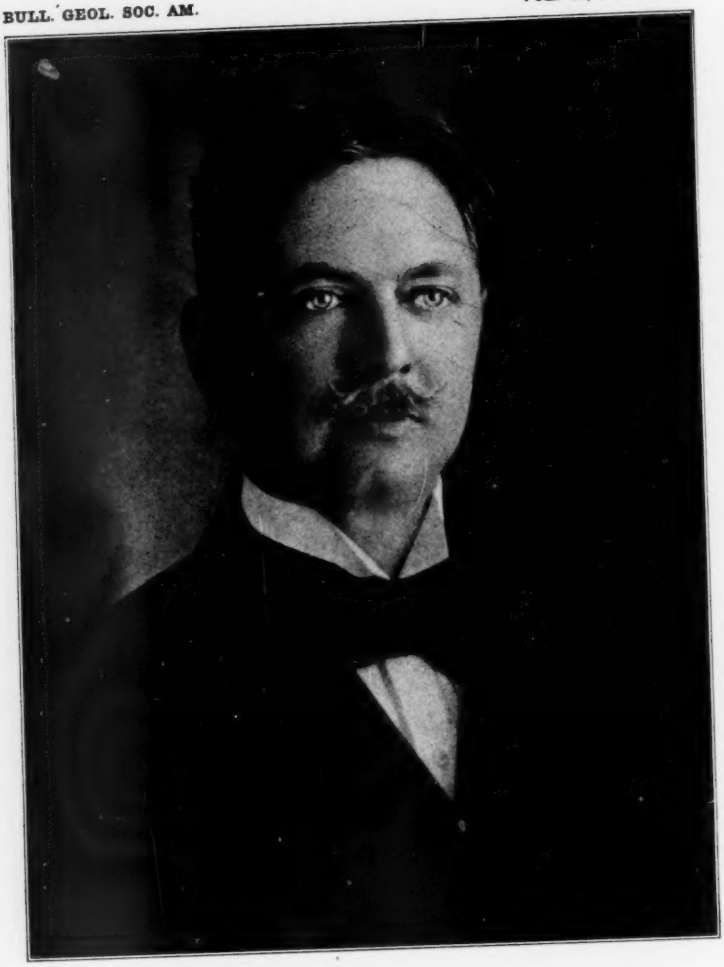

Yours truly
Earle Sloan

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MEMORIAL OF EARLE SLOAN [1]

BY THOMAS WAYLAND VAUGHAN

Earle Sloan was born on Cherry Hill Plantation, near Old Pendleton, South Carolina, on October 18, 1858. His father, Col. John Bayliss Sloan, was a planter and cotton factor and during the Civil War was colonel of the Fourth Regiment from South Carolina. His mother was Miss Mary Seaborn before her marriage to Colonel Sloan. On both his father's and his mother's side be belonged to the landed gentry of the Old South and was trained in the traditions, manners, and customs of the social class which was his by inheritance. He died, after a prolonged illness, on August 19, 1926.

When Sloan was eight years old his parents moved from Old Pendleton to Charleston, where he had all his schooling before going to the University of Virginia. For five years he attended a local classical school of high repute, conducted by A. Sachtleben, and later he was for three years a student at the Carolina Military Institute. He entered

[1] Manuscript received by the Secretary of the Society June 25, 1928.

the University of Virginia in 1878, graduated three years later, and remained a year afterward for graduate study. At the university he paid special attention to chemistry and geology, and according to reports of his old associates, he did excellent work in both subjects. Parts of his vacations were spent in the field, under the tutelage of Prof. W. M. Fontaine, the eminent paleobotanist of the University of Virginia.

After leaving the University of Virginia, Sloan's life was varied. The first year was spent in visiting mines and examining industrial plants. During 1883 and 1884 he was engaged in reporting on the properties of the Norfolk and Ouray Mining Company of Ouray, Colorado. He then transferred his activities to Alabama and devoted three years to the study of the Carboniferous and Silurian formations of that State, paying special attention to the exploration and development of coal and iron deposits. In 1886 he and William H. Echols, later professor of mathematics at the University of Virginia, formed a partnership under the name "Echols and Sloan, engineers, civil and of mines," and the firm in 1886-1887 carried out several different kinds of engineering work, such as building railways, laying off the town of Ensley, and examining mines and mineral prospects. The partnership was terminated in 1887 by Mr. Echols accepting the professorship of engineering in the Missouri School of Mines, but the friendship formed endured throughout Sloan's life. For a time he was engineer of the Tennessee Coal, Iron and Railroad Company.

The work in Alabama was followed by two years' study of the bauxite and iron deposits of northwest Georgia and additional investigations in Alabama. The phosphate deposits of South Carolina engaged his attention for years. He was the superintendent of the Edisto Phosphate Works, head of the Archdale Phosphate Mines, and, with Mr. C. O. Witte, he owned the Etiwan Works. As Sloan was chemist as well as geologist, he devoted much attention to the technology as well as to the geology of the phosphate deposits, and to him is credited in large measure the development of the South Carolina phosphate industry.

The foregoing paragraphs indicate major activities. He also undertook examinations for short periods in Wyoming, North Carolina, Florida, Tennessee, and Arkansas.

Sloan's first work without any commercial purport was as an assistant on the United States Geological Survey in Major C. E. Dutton's study of the Charleston earthquate of 1886. The value of Sloan's contribution to this investigation can best be indicated by quoting Major Dutton's own words in the preface to his report:

"I must, however, mention with special gratitude the work of Mr. Earle Sloan, of Charleston, who undertook the investigation of the epicentral tract of the earthquake. With great labor and patience he studied the ground for two months, and subsequently reviewed portions of it, gathering together a large amount of information of the kind that was wanted and submitting it in a form capable of being used intelligently. Without his researches some of the most valuable results of the study of this earthquake would never have been realized." [2]

In 1901 Sloan accepted appointment as State Geologist of South Carolina and worked for the State in that capacity until 1911. As the appropriations were very small, the field-work was prosecuted very largely at his personal expense, and he was led to remark that he found the position of State Geologist "an expensive dissipation"; it cost him time as well as money. While State Geologist he examined most of the geologic formations of the State and published several valuable papers on the clays, other mineral resources, and the geologic formations, particularly of the Coastal Plain. He was also interested in the metamorphic rocks of the Piedmont province. Although his published papers record important contributions to knowledge of the geology of South Carolina, actually his greatest contributions were through the assistance he rendered others. His knowledge of the detail of the different localities and of specific exposures was truly astonishing. The unraveling of the stratigraphic relations in South Carolina is no simple matter. The bedrocks are mostly concealed by surface deposits of several different kinds and can be traced only with difficulty or not at all. Correlations must be based mostly on very accurate studies of the fossils. Sloan was utterly untiring in guiding first one specialist and then another over the Coastal Plain, showing him significant exposures, helping collect fossils, and in every way making his own rich fund of information available for use in deciphering the geology of his native State. He was several years ahead of some of his colleagues in recognizing the correct interpretation of some obscure relations. An instance of this was his contention that a certain formation was Oligocene and was separated from the underlying Eocene Cooper marl by a disconformity. His discovery of the skull of an archaic toothed whale, named by Dr. Remington Kellogg [3] *Xenorophus sloani*, at Woodstock station, in Berkeley County, South Carolina, supported his opinion. It is true of numerous scientific men that their greatest work has been in the personal assistance they have rendered others, rather than in papers published under their own names, and among these

[2] U. S. Geol. Survey, 9th Ann. Rept., 1889, p. 210.

[3] Smithsonian Misc. Coll., vol. 76, pub. 2723, 1923, p. 2.

should be counted Earle Sloan. It is probable that his early experience as an engineer had accustomed him to communicating his ideas by special reports and oral discussion, rather than through the medium of formally published papers; but, be that true or not, the fact stands that Sloan was one of the principal contributors to knowledge of the geology of South Carolina.

Another side of Sloan's character was his interest in matters of public welfare. One of the subjects to which he devoted much attention was the water supply of Charleston, advocating that the city get its supply from Edisto River.

On October 11, 1894, Sloan married Miss Alice Reeves Witte. She, three daughters, Carla (Mrs. S. F. Shackelford), Elizabeth (Mrs. C. L. Mullally), and Miss Lottie Sloan, and one son, Earle Sloan, survive him.

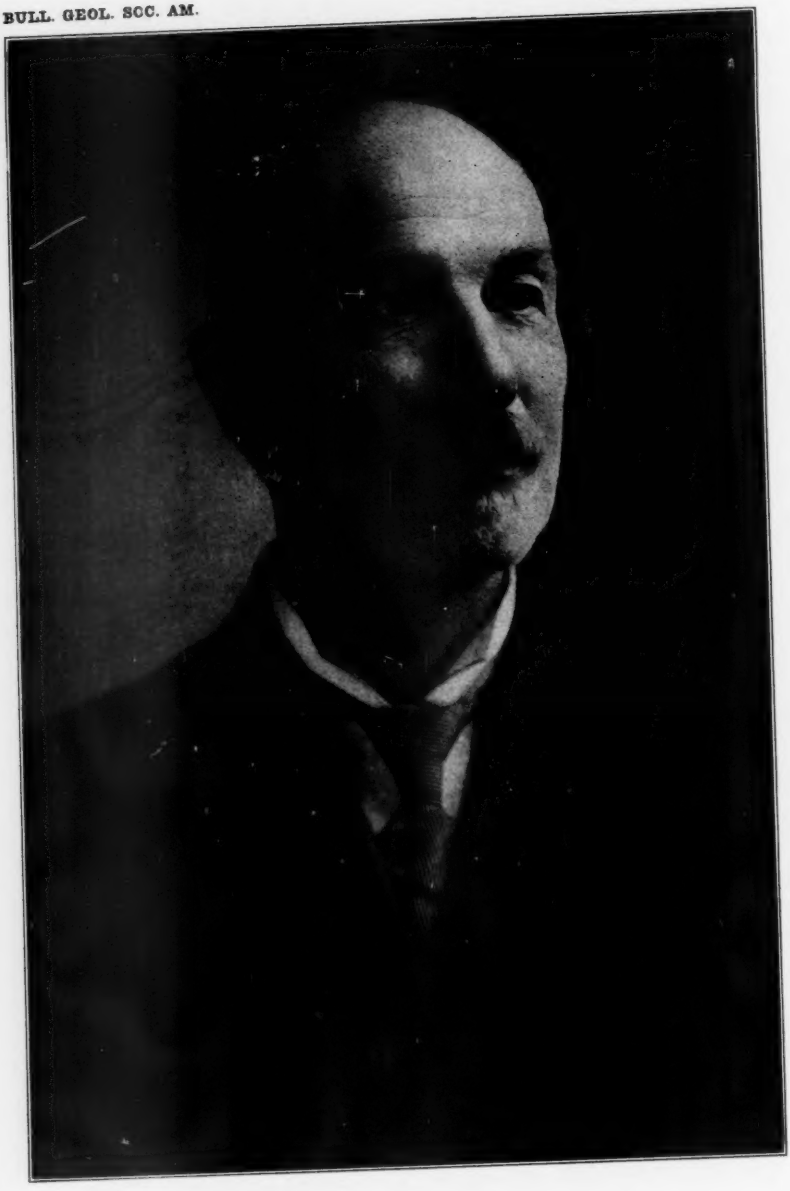
Sloan was a man of the highest type of character. His old friend, Prof. W. H. Echols, says of him:

"His rare ability, absolute integrity, his remarkably sound judgment, backed by his unusual technical skill and knowledge of geology and chemistry, made him most valuable in his profession. The combination of thoroughly scientific knowledge and practical common sense and sound judgment made him one of the most reliable and sought after men in his field of work."

Besides his scientific attainments and sound judgment in business and other affairs of life, Sloan possessed a genial, lovable personality, which made him a delightful companion, whether in his own charming family circle or on field trips in the woods and swamps of the back country. He was an accomplished raconteur and had an apparently inexhaustible fund of amusing stories and anecdotes. The writer of this article knew Sloan intimately for years and spent an aggregate of months in the field with him, as well as having enjoyed the hospitability of his home many times. Sloan was a perfect host and companion. His interests were wide and varied, including architecture, gardens, and other kinds of art. He was an authority on all things pertaining to South Carolina. He was so broad in his sympathies for those things that are considered the better things of life that in looking back over the experiences with him the courteous, kindly, cultivated gentleman stands out above the man of scientific attainments. He had friends not only where his home was, but all over the State. His loss is, and long will be, keenly felt, but he greatly enriched the lives of those who were so fortunate as to have known him.

Besides being a life fellow of the Geological Society of America, Sloan was a member of the Sigma Chi fraternity, Phi Beta Kappa, the American Association for the Advancement of Science, the American Museum

UNIVERSITY OF CALIFORNIA



J. S. Diller

of Natural History, honorary member of the Philosophical Society of the University of Virginia, president of the South Carolina branch of the University of Virginia alumni, and honorary curator of geology of the Charleston Museum. He was for a time a member of the American Institute of Mining Engineers and of the Association of State Geologists.

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MEMORIAL OF JOSEPH SILAS DILLER [1]

BY A. J. COLLIER [2]

Joseph Silas Diller, one of the few remaining original Fellows of the Geological Society of America, died November 13, 1928. For nearly half a century he had been an eminent Federal geologist and explorer and he was the author of numerous papers of high quality. Mr. Diller was born near Plainfield, Pennsylvania, August 27, 1850. His parents were of sturdy German-Swiss stock, being descendants of Francis Tueller and other Mennonites, who, seeking a land of religious freedom and tolerance, migrated from Switzerland and settled near Lancaster, Pennsylvania, in 1754. The passport of Francis Tueller from Switzerland is written in French and his son Peter was the first to sign the name Diller in its present form. His ancestors in America were self-respecting, hard-working, thrifty farmers, who resided for three generations near the Diller Church, in Cumberland County, Pennsylvania, where a stone to the memory of Francis and Anna Tueller has been erected.

[1] Manuscript received by the Secretary of the Society March 16, 1929.
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[2] The writer wishes to acknowledge his deep indebtedness to Mr. Diller's many friends on the Geological Survey and to his family for many of the facts and incidents related in this paper.

Mr. Diller attended the public school near Plainfield and the Academy at Greason. At 21 years of age he entered the State Normal School at Westfield, Massachusetts, as a student and two years later he secured the position of teacher in that institution, which he held until 1877. While here he became interested in geology through one of his teachers, Mr. J. G. Scott, who had been a pupil of Agassiz. His first contribution to geology, entitled "Westfield during the Champlain period," was published in 1877. During the summer of that year he entered Harvard University, being enrolled in the summer school for a geological excursion led by Professor Shaler. On this excursion he fell in with another ambitious student, William Morris Davis, and, being of about the same age and inclination, one of Mennonite the other of Quaker ancestry, they tramped together and made some interesting side trips that were not on Professor Shaler's schedule.

Mr. Diller continued as an undergraduate student at Harvard until 1879, when he received the degree of B. S. from the Lawrence Scientific School. For the next four years he was engaged in postgraduate studies at Harvard and Heidelberg, Germany, specializing in petrology. At Harvard, under Professor Wadsworth's guidance, he became interested in a study of the felsites and published several short papers relating to these rocks as exposed in the vicinity of Boston. At Heidelberg, Mr. Diller became very much attached to Prof. H. Rosenbusch, and in his account of the "Francis Diller family" he referred to him as his "dear old friend and teacher." While at Heidelberg, in 1881, Mr. Diller was engaged as geologist of the Assos Exposition to search for the ruins of the ancient city of Assos, Asia Minor. In association with several noted archeologists, he tramped over the mountains and plains of the Troad, and among other things he studied the crater of Assos. The detailed report of his work on this expedition was published in 1882, in the Papers of the Archæological Institute of America, and notes on the geology of the Troad were published in Science, volume 2, August, 1883.

On June 5, 1883, Mr. Diller married Laura I. Paul, of Greason, Pennsylvania, a town about a mile from Plainfield. She had been one of his pupils in the public school at Greason and later took up special work at Wellesley while he was at Harvard. In 1894 they built their home on the brow of the Belmont Street hill, in Washington. The living room, on the second floor, opens out on a broad veranda shaded by two great oak trees and commands a superb view of Washington, with Arlington and the Virginia hills in the distance. It was here that the greater part of their lives was spent and many of their friends were entertained.

In 1883 Mr. Diller had to decide between a university career and that of a professional field geologist. Harvard University called him, and his friends in the newly organized United States Geological Survey asked that he cast his lot with them. He chose the latter course, which he pursued to the end, apparently without regret, for in later years he again declined tempting teaching positions, one at Stanford and another at Harvard.

He was appointed an assistant geologist on the Survey in July, 1883, was promoted to the rank of geologist in 1888, and held this rank until he retired from active work, on December 31, 1923. His first Survey assignment was a study of the Cascade Range under the direction of Captain C. E. Dutton. He ascended Lassen Peak and Mount Shasta, in California, and Mount Scott, Union Peak, Mount Theilson, Diamond Peak, and The Three Sisters and visited Crater Lake, in Oregon. With his assistant, Ensign E. E. Hayden, of the United States Navy, he rolled logs down from the rim of Crater Lake, lashed them together with ropes to make a raft, and paddled out on its clear waters to inspect the small cone on Wizard Island. His was the third expedition to reach the island.

In climbing one of the Three Sisters he met with a serious accident which nearly ended his career. His assistant, always more venturesome than he, stood too near the edge of a high cliff which gave way, throwing him far down the mountain side, where he lay with a broken leg, unable to move. Mr. Diller climbed down among the rolling rocks loosened by Hayden's fall and moved the injured man to a place of comparative safety. He then summoned the cook and teamster, and they had just started to carry the wounded man to camp when a rolling rock struck Mr. Diller in the face, knocking him farther down the mountain. The cook and teamster gave him up for dead and again started for camp, but before they were out of sight they saw him move. Hayden lost a leg and Diller always bore the scars of this adventure. In reporting on Mr. Diller's work that summer, Captain Dutton said:

> "Although often working under adverse circumstances, he achieved the main object of his reconnaissance, for he disclosed how the grand theater of volcanic activity now extinct may best be studied in the future."

In 1884 Mr. Diller began a detailed study of Mount Shasta and the surrounding country, which was continued from year to year and extended, until eventually it included nearly all of northwestern California and western Oregon and involved the Sierra Nevada, the Cascade Range, the Klamath Mountains, and the Coast Ranges of California and Oregon.

His final paper of this series was given to the public in 1924, the year after his retirement from active work.

In 1883 Mr. Diller introduced the then comparatively new methods of research in microscopic petrography in the United States Geological Survey. His work at Harvard under Wadsworth and at Heidelberg under Rosenbush had prepared him well for this responsibility. At Heidelberg he had been one of the first Americans to study under Rosenbush, then one of the world's foremost instructors in the microscopic physiography of rock-making minerals. The geologists of America were just beginning to use the microscope in the study of rocks. Other American geologists working along the same lines were Prof. G. H. Williams, of Johns Hopkins; Dr. C. W. Cross, of the Geological Survey; Prof. L. V. Pirsson, of Yale; Prof. J. P. Iddings, of Chicago, and Dr. H. S. Washington.

The identification of rocks for many geologists was done under Mr. Diller's personal direction, and many specimens of rocks and minerals were submitted to the petrographic laboratory the determination of which was sometimes a matter of considerable interest and scientific value. Such determinations often took up much time, but resulted in short published articles, like "Volcanic sand from Unalaska, Alaska," "Fulgurite from Mount Thielson, Oregon," "Iron from the new volcano on Bogosloff Island, Alaska," and "Notes on the peridotite of Elliott County, Kentucky."

A collection of typical rocks of America, to be distributed as the "Educational Series of Rocks" to the colleges and universities of America, had been started in 1882, under the direction of Major Powell. Several geologists had been named for this work, but little had been accomplished. The completion of the series and the preparation of the bulletin to accompany it was assigned to Mr. Diller soon after he came to the Survey. The plan was to collect and distribute at least 200 sets of one hundred hand specimens each, together with thin-sections wherever possible. The bulletin describing the collection was published in 1898 and was reprinted in 1902. It consists of an introductory chapter on the study and classification of rocks and a description of 156 typical specimens. Seventy-four of these descriptions and the introductory chapter of the book were written by Mr. Diller, while eighty-two are credited to seventeen other geologists. By 1899 250 full sets of the "Educational Series of Rocks" had been distributed, and when Mr. Diller was relieved of this work, in 1903, after 19 years of service, he had collected and distributed nearly 300 standard collections of rocks and had written a very satis-

factory, though elementary, textbook of rocks for all of the geological students of America.

Although Mr. Diller first climbed Mount Shasta in 1883 and in 1884 he spent a large part of the season working out the details of that mountain, it was not until 1895 and 1896 that he was able to complete a report on it. This was published as a National Geographic Monograph by the American Book Company.

He first visited Lassen Peak in 1883. In 1885, 1886, and 1887 he returned to complete the detailed survey of the mountain and vicinity. His work was held back by the need of accurate topographic surveys, but his report on the "Geology of the Lassen Peak District" was published in 1889. In 1885 he was visited in the field by Captain Dutton, who was so enthusiastic at what he saw that he published an account of the cinder cone near the peak and called it the latest volcanic eruption in the United States, putting the date as January, 1850. Mr. Diller on revisiting the locality found unmistakable evidence that the time of the latest eruption was surely much earlier than 1850, for though stumps of the trees killed in that eruption are still standing, the living trees which have grown since the eruption are over 100 years old. He decided that the time of the then latest eruption may have been as much as several hundred years ago. He was fortunate enough to be near at hand in 1914, when the volcano again became active, and he revisited it and published accounts of its activity. In all he published 16 separate papers in the last 40 years describing sundry features of this mountain, and though its latest eruption was mild in comparison with the gigantic eruptions of the past, it surely is "our most active volcano."

In the years from 1888 to 1895 his field-work consisted of detailed surveys of special areas in northern California and reconnaissances covering much of the Pacific coast, the general purpose of which was to establish the relations of the Sierra Nevada, Cascade, and Klamath Mountains to the Coast Ranges of California and Oregon. With this in view, he published, among other papers, "Notes on the geology of Northern California," "Klamath Mountains," "Topographic development of the Klamath Mountains," "Structure and age of the Cascade Mountains," and "A Tertiary revolution in the topography of the Pacific coast."

Mr. Diller returned to Crater Lake in 1896 to make a more detailed study of its geology. In the meantime the lake had been explored and sounded by Captain Dutton and the topography mapped by Mark B. Kerr. In taking up this work Mr. Diller gave credit to Captain Dutton as the first to discover the novel and salient features of the lake and its

environs. He supported Captain Dutton's theory that the depression occupied by Crater Lake is not a typical crater, but a caldera, a collapsed volcanic cone. In proof of this concept of the origin of the depression, Captain Dutton had cited the radiating canyons that are truncated abruptly at the rim of the caldera; but Mr. Diller had another and more convincing proof in the unmistakable glacial striæ that he found radiating outward at the very edge of the rim—most satisfying evidence of the former existence of a Shastalike peak over the site of the present lake. In answer to the question as to whether this vanished mountain had collapsed or had disappeared through the agency of a great explosion, Captain Dutton had called attention to the absence of the debris that should be expected if the mountain had exploded; but Mr. Diller had found a place where, in the mountain's last eruption, a thick lava flow had cooled enough to have a solid crust, but a still viscous interior, and when the mountain collapsed and sank away, the viscous portion of the stream flowed down the inner slope of the caldera. The origin of the depression was no longer speculation with Mr. Diller; it was fact. The Mazamas, convinced that this was the true history of Crater Lake, applied their name to the vanished peak and called it Mount Mazama, with appropriate ceremonies.

Congress recognized the importance of the lake and the surrounding remnants of Mount Mazama as an educational and scenic feature and created a national park embracing them on My 22, 1902. Anticipating this action, Mr. Diller, accompanied by Professor Patton, spent the season of 1901 reviewing the geology of the region. The results of this review appeared in 1902 as Professional Paper Number 3 of the United States Geological Survey. Other publications of his on this topic are his annual address as the retiring President of the Geological Society of Washington, in 1902, "The wreck of Mount Mazama;" a very popular "Geological History of Crater Lake," written for the Interior Department in 1912, and a reply to the question, "Did Crater Lake, Oregon, originate by a volcanic subsidence or an explosive eruption?", published in 1923, the year he retired.

Mr. Diller is the author of a number of folios and other papers on southern Oregon and northern California, still the principal source of our knowledge of the geology of that portion of the United States. Most of the geologic mapping for the Roseburg folio, in the northern part of the Klamath Mountains, was done in 1896. The mapping for the Coos Bay folio, in the Klamath and Coast Range of Oregon, was done in 1897. It is represented by a report on the Coos Bay coal field in the

Nineteenth Annual Report of the United States Geological Survey and the folio text. The mapping for the Port Oxford folio, in the Klamath Mountains of Oregon, required the major part of three seasons, and the mapping for the Redding folio, in the Klamath Mountains of California, which had been begun a good many years before, required for its completion four years of systematic field-work. Its publication was preceded by short papers describing copper, iron, limestone, and mineral resources of the Redding Quadrangle. The geology of the Redding Quadrangle, surveyed in 1901 to 1904, was published in 1906. The Riddle folio, by Diller and G. F. Kay, was published in 1924, after Mr. Diller's retirement. The mineral resources of the Grants Pass Quadrangle and the Galise-Kerby-Waldo region, in Oregon, and the auriferous gravels of the Weaversville Quadrangle and Trinity basins, in California, were published in the years from 1910 to 1920.

Asbestos, talc, soapstone, and chromic iron ore were assigned to Mr. Diller for the preparation of reports for the Mineral Resources volumes and he reported on the annual production of these minerals from the years 1907 to 1919. Being specially interested in asbestos, he visited the most promising localities, scattered over the country from Vermont to the Grand Canyon in Arizona, and in 1911 published a paper on the types, modes of occurrence, and important deposits of asbestos in the United States.

During the World War chromic iron ore, which ordinarily is of little value, on account of European competition was in great demand. Mr. Diller's reports showed that large deposits of chromite were to be found in Oregon and California, and he went into the field in search of this mineral. The large outcrops were "gophered" out and shipped away to aid in winning the war.

In anticipation of the San Francisco World Fair, on the completion of the Panama Canal, in 1915, the geologists of the Survey were asked to prepare guidebooks to be placed on the transcontinental railroads leading to San Francisco. To Mr. Diller fell the lot of writing the guidebook of the Shasta Route, from Seattle to San Francisco, and in this work he spent the season of 1914. Many facts about this route were already familiar to him, for he had traveled it many times and had watched its development since 1883, when he moved his camp equipment from Mount Hood to California over the muddy roads of Oregon. In this guidebook, written in popular style, he tells much of the history of the development of the Pacific coast, both geologic and recent, as suggested by what may be seen from the car windows in passing. His

descriptions of Mount Shasta and the Sacramento Canyon from Mount Shasta to Redding, with the notes on the old California to Oregon stage road, the good hunting and fishing places, and the gold and copper mines, are exceptionally fine.

Mr. Diller's work in the field was systematic and painstaking. He would weigh every material statement from every possible point of view and would review any part of his work that seemed doubtful or had been questioned. He was not a debater, but an ardent seeker after the truth, a real scientist, even though the always welcome additional facts might result in his having to abandon some of his pet theories. Although primarily a petrographer, his work was equally sound in stratigraphy, structural geology, physiography, and economic geology. He was a great collector of fossils and relied on the reports of the paleontologists for guidance on questions of correlation and age.

Mr. Diller was not an adept at any of the games of chance or skill. His principal recreation while in Washington was in walking, and Sunday afternoons he was very apt to propose a walk from his home to the Zoological Park to renew his acquaintance with the animals. At Harvard he had tried his hand at acting and several times appeared on the stage in the rôle of a citizen or soldier, etcetera, with noted actors. He used to tell with great glee of his embarrassment when in playing with Joseph Jefferson he had seen Miss Paul, his fiancée, sitting near the front row with other attractive ladies from Wellesley. In the activities of the Pick and Hammer Club, an informal social and scientific club of Washington geologists, he was always ready to help in any way possible, often participating successfully in annual frolics.

In camp Mr. Diller was very fond of casting a fly, and usually he had a fishing rod somewhere in the outfit. The party would work incessantly for 9 or 10 days, and then perhaps would make camp beside some attractive stream and Mr. Diller would proclaim that the next day would be Sunday. He usually got the biggest string of trout, and could tell about some particularly fine holes, where in a very few minutes he caught all the trout required by the party, but, as is customary in such stories, the biggest ones got away.

Probably the two monumental works of Mr. Diller's career are his exploration and description of Lassen Peak and Crater Lake. The Mazamas, whose motto "Nesika Klatawa Sahale," signifies mountain lovers of the land where the Chinook Jargon was spoken, claimed him as an honorary member, and by the people of the Pacific coast generally no scientist was held in higher repute and esteem than Mr. Diller.

His many field assistants, who enjoyed the close intimacy of camp life with Mr. Diller, always found him thoughtful, considerate, and generous, not a driver but a leader, who never expected more of them than he was ready to give himself. They regarded him first of all as a thorough and sincere friend. He was always ready to assist in the solution of difficult problems and he set for them an example of fairness and honor, both in the interpretation of scientific facts and in his dealings with his fellow men. When the conditions of camp life were vexing, he kept the same evenness of temper as when all went well. Association in camp with men like Mr. Diller is one of the most cherished rewards of the Survey life.

George Otis Smith, the present Director of the Survey, said, in a letter written in 1924, at the time of Mr. Diller's retirement:

"I can not let the fact of your retirement pass without attempting to express something of what I believe to be the attitude of your associates in the Survey toward you by reason of your long association with them. We all recognize you as one of the living foundation stones on which the Survey's reputation rests. During 40 of the 44 years of the Survey's existence you have been a valued member of its staff. During all of that period you have given to it, and, through it, to geologic science and to the people of the United States, able, highly trained, unselfish, and wholly disinterested service.

"You have your share of monuments in the form of Survey classics to which your name is attached as author, but, more than this, you are entitled to far larger share than most of us of credit for that most important and most helpful type of indirect and officially unrecognized and unrecognizable service rendered through a never-failing readiness to aid and inspire your associates, old or young, in their own problems, thus giving to them and to the Survey through them the benefit of your own wide experience, thorough training, and fine scientific spirit. You may remember that I had the opportunity of close-range observation of you at work, and I venture to say that no man who has ever been on the Survey staff has rendered more frequently and rendered more cheerfully this type of indirect assistanc which, by its very nature, can not appear in the cold official records, but is forever recorded in the hearts of all of us."

Coming on the Geological Survey in the fourth year of its existence, he had been associated with many of the foremost geologists of America, and, with his high scientific standards and his wholly unselfish and kindly personal characteristics, he constantly exerted a quiet but strong and most beneficial influence on the development of that organization.

He has served as Vice-President of Section E of the American Association for the Advancement of Science, Vice-President of the Geological Society of America, President of the Geological Society of Washington, Secretary of the Washington Academy of Sciences, Secretary of the

Washington Philosophical Society, corresponding members of the Appalachian Mountain Club, member of the American Institute of Mining and Metallurgical Engineers, member of the National Geographic Society, and honorary member of the Mazamas. In recognition of his service to geology, medals were conferred on him by the Paris International Exposition in 1900 and by the Panama Pacific International Exposition in 1915. He was for many years a member of the Cosmos Club and of the First Congregational Church of Washington.

He retired from active work on December 31, 1923, and died at his home in Washington, November 13, 1928. He is buried in the village cemetery at Plainfield, Pennsylvania, not far from the place of his birth.

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ADDRESS OF WELCOME BY HENRY FAIRFIELD OSBORN

Prof. Henry Fairfield Osborn, President of the American Museum of Natural History and President of the American Association for the Advancement of Science, was in attendance at this opening session and addressed the Society, extending the welcome of the American Museum of Natural History to the use of its rooms and accommodations for the various sessions scheduled by the Geological Society of America and the affiliated societies.

MR. PRESIDENT, LADIES AND GENTLEMEN:

It is a great honor to receive the Geological Society of America and a great pleasure to do all we can, not only to make this meeting interest-

ing and agreeable, but to have it mark a real step forward in the science of geology. Under the direction of Dr. Chester A. Reeds, all our scientific and administrative staff have cooperated to perfect the arrangements, and we are sorrowful that at the last moment he was called away to undergo a serious operation.*

Geology has been the foster parent, both of paleontology and of biology, as shown in the relations of Charles Lyell and of Charles Darwin. Consequently it has been arranged that this congress of all the natural sciences opens with two general evening addresses by Prof. Bailey Willis, retiring President of this Society, on "Continental genesis," and by Prof. Charles P. Berkey, on "The geology of Mongolia."

It happens that this is the centenary of the glacial theory, for just a century ago the two preliminary papers of this epoch-making theory were published. Accordingly, one afternoon is devoted to a symposium by some of the most eminent glaciologists of America and of Europe. Another special feature has been the preparation of a new equal area world map in four projections, which are severally adapted for plotting north polar distribution, continental distribution, and oceanic distribution. The principal new feature of these maps is that North America finds its proper and natural place east of Asia.

The attention of the members of the Geological and Paleontological societies is especially called to the serial plan of arrangement of six great prehistoric exhibition halls on the fourth floor, beginning with dawn of life on the earth in the old Geology Hall, passing through the successive epochs, and culminating in the Hall of the Age of Man. The coming construction of the new African section of this building will make possible this great and unique serial arrangement in prehistoric order on an advanced scale.

Session for the Presentation of Scientific Papers

TITLES AND ABSTRACTS OF PAPERS

SOME HURONIAN PROBLEMS

BY ANDREW C. LAWSON

(Abstract)

Evidence is presented indicating that the Killarney granite is not Keweenawan or post-Keweenawan in age. There appears to be no real objection to correlating the Killarney granite with the Algoman granite. The Sudbury Series is shown to be post-Mississagi and therefore can not be pre-Huronian.

* The operation, performed at the Presbyterian Hospital, was successful and Dr. Reeds has recovered.

as supposed by Coleman. The stratigraphic classification of the series is discussed. Two resurrected peneplains are recognized north of Lake Huron: one on which the Huronian rocks were deposited and which was evolved in the epi-Laurentian interval; and one which truncates both the folded Huronian and the Killarney granite and was evolved in the Eparchean interval. Two periods of development of granite alternating with two periods of peneplanation afford an excellent basis of correlation of the general section north of Lake Huron with that northwest of Lake Superior.

Read by title.

ORBICULAR GRANITES

BY J. J. SEDERHOLM

(*Abstract*)

The discovery of several new orbicular granites in Finland has induced the writer to make a restudy of the origin of these structures. It is concluded that they have always been formed around a nucleus which was either a xenolith or a crystal or crystal aggregate. Both the liquation theory as an explanation of the origin of the spheroids and the eutectic proportion theory are rejected as inadequate.

In one case studied by the writer no difference in chemical composition between the spheroids and their matrix was found, but in certain other cases the nuclei of the spheroids were surrounded by a zone of magma that remained fluid longer than their respective outer shells, through which it may have erupted.

The spheroids are not simply remelted fragments, because fragments and spheroids exist side by side with no gradation between them. The spheroids with radially arranged feldspar laths are analogous to spherulites, whereas those consisting of concentric layers, often varying regularly in composition, are interpreted as having formed by rhythmical deposition with regularly changing composition of the magma in contact with the shells.

High viscosity in the magma, because of its richness in plagioclase, is postulated, and the abrupt termination of the crystallization of the spheroids is explained by the concentration of the water contents of the magma in the mother liquor. As a result of this the matrix (or "cement") is frequently pegmatitic and often shows a marked segregation of femic and salic portions.

Deformation of these spheroids is common in these rocks. It has generally occurred while they were not yet entirely consolidated. One of the orbicular granites studied exhibits real cataclastic structures, which were probably due to stresses directly related to the same general period of igneous activity.

Brief remarks were made by Messrs. Alfred C. Lane, Andrew C. Lawson, and C. W. Brown, with reply by the author.

GEOLOGY OF CEYLON

BY FRANK DAWSON ADAMS

(*Abstract*)

The island of Ceylon lies immediately to the south of the Indian Peninsula, being offset from it a little to the east. It has an area of approximately 25,000

square miles, or one-half that of England. The island consists of a low coastal plain from which in its south central part there rises abruptly a block of high land culminating in peaks, of which Adams Peak (7,353 feet) is the best known and Pedurutalagala (8,292 feet) is the highest. The coastal plain is very wide to the north, but becomes narrower elsewhere, especially along the south coast.

Three distinct plains of denudation can be clearly recognized in Ceylon. The coastal plain, about 200 feet above sealevel, a second plain at about 2,000 feet, and a third at 6,000 feet above sealevel.

The island is composed almost entirely of crystalline rocks of Archean or Precambrian age. In the extreme north these are overlain by limestones of Miocene or later age. At one point on the northwest coast a very small area of Jurassic rocks lies on the surface of the coastal plain.

The ancient crystalline rocks resemble in many respects the Grenville Series of the Canadian Shield. They are largely biotite gneisses, interstratified with which are at least two great beds of white crystalline limestone, often dolomitic, with associated beds of quartzite and of sillimanite-bearing rocks of undoubted sedimentary origin. Charnockite and allied rocks are present also in large amount, especially in the higher parts of the island. The petrography of these rocks is described, and is illustrated by a series of chemical analyses, the first that have been made of the rocks of this island. In structure Ceylon is a portion of a great syncline, deeply eroded, closed on the south, open to the north, where it plunges beneath the Miocene cover. The foliation, displayed more or less distinctly by all the crystalline rocks, runs down the west side of the island, sweeps around the south and up the east side. It is parallel everywhere to the coastline, whose course and the pear-shaped form of the island have been determined by its direction. The limestone bands conform to it. This great battered remnant of a huge syncline whose axis strikes north and south, parallel to the Coromandel coast of India, has been deeply wasted by secular decay. It would have long since disappeared under this influence, had it not been at least three times raised to new elevations above the sea. At least 10,000 feet of gneiss have been rotted away over the greater part of the surface of the island. This process is still at work, mantling much of the island with red lateritic clay and etching out its structure in a most wonderful and striking manner. The island is a very interesting remnant of Gondwana Land, most of which now lies beneath the waters of the Indian Ocean.

Brief remarks were made by Prof. Alfred C. Lane.

MEANING OF THE EARTH'S RIGIDITY

BY REGINALD A. DALY

(*Abstract*)

Experiments of Feild and Royster with many silicate melts show that each of these had rigidity, true elasticity of form, when exposed to small stresses for a considerable interval of time. The high rigidity of the earth has been estimated only through the reactions of the planet and of its successive shells against the stresses developed by body tides, by earthquake shocks,

and by the straining which accounts for the period of the free variation of latitude. All three kinds of stress are, at maximum, small. Hence the rigidity of the earth does not seem necessarily to imply crystallinity for its material at any depth below the bottom of a relatively thin crust.

Brief remarks were made by Prof. Bailey Willis.

SOLVENT DENUDATION OVERESTIMATED—GEOLOGICAL AGE UNDERESTIMATED[1]

BY ALFRED C. LANE

(Abstract)

River water analyses are rarely representative of the water in times of flood, when the suspended matter is most and the dissolved matter least in grams per liter, but the bulk of the run-off of most streams is during a small fraction of the year, in times of flood. Consequently, multiplying the run off by the results of such analyses, even if they are monthly averages, gives much too high amounts. Recent work by W. D. Collins on the Colorado River enables us for the first time to get a quantitative idea of the error, which may make solvent denudation 2.4 times too great.

Making allowance for this, as well as for cyclic sodium and for less denudation in times of peneplanation, when the continents were smaller, will give geologic ages of many hundred million years, quite comparable with the figures obtained from atomic disintegration.

Brief remarks were made by Messrs. W. H. Hobbs and Alfred C. Lawson.

CORRELATION OF TERTIARY MOUNTAIN RANGES IN THE DIFFERENT CONTINENTS

BY FRANK BURSLEY TAYLOR

(Abstract)

In North America, three main ranges or systems of ranges seem well defined: (1) The Rocky Mountains, (2) the Cascade Mountains, including the Sierra Nevada, and (3) the Coast ranges. All three take northwesterly courses in the western part of the continent. The Rocky Mountains are the farthest inland and the oldest. They are an older range, rejuvenated by uplift and moderate folding mainly in the late Cretaceous and early Tertiary. The Cascade Range lies nearer to the Pacific coast and is of younger age. The closely set Coast ranges lie next to the ocean throughout, forming a chain of islands between Puget Sound and Mount Fairweather. They are the youngest of the three and are still actively in the making. On account of the simplicity of their relations, the Tertiary ranges of North America are taken as the basis of correlation.

Alaska, west of the great mountain angle, belongs structurally to Asia. At this angle all three ranges turn to westerly courses, the Rockies running

[1] Published in the February issue of the American Journal of Science.

west as the Endicott Range to Bering Strait. The Cascade Range, swinging in the wide curve of the Alaskan Mountains, finds continuation in the great festoon arc of the Aleutian Islands. The Coast Range turns to the southwest in the Chugach Mountains and continues in the Afognak, Kodiak, and Trinity Islands. Thus, the Rockies and the Cascade Range make close contact with continental Asia, while the Coast Range appears to be lost in the sea. The Rockies and the Cascade may be followed into Asia with little likelihood of error. The Rockies continue first in the Stanovoi Mountains, and farther on in the Great Khingan. Bending to the west through smaller ranges, it reappears in the Tian Shan, and from the Pamirs it appears to run on in the Hindu Kush, the main line trending toward the Caucasus, another line bending around the south end of the Caspian Sea.

The Cascade Range, so clearly continued in the Aleutian arc, seems to extend through the whole line of festoons to Luzon, in the Philippines. The main line seems to pass on through Palawan into Borneo. Farther on it follows the Malay Peninsula northward and seems to continue in one of the back ranges of the Himalaya system. Beyond this its course to the west seems uncertain, at least as far as southeastern Persia. Farther west its course seems fairly clear through the Zagros and Taurus Mountains, through the Cyclades Islands, and through the Pindus Mountains to the Julian Alps, beyond which it appears to merge into the main Alpine arc. Farther west it is not yet clearly identified, unless it reappears in the Sierra Nevada-Balearic Islands line in Spain.

Trending toward the southwest, the Coast Range plunges under the ocean at the Trinity Islands. No feature on the ocean floor suggests its course beyond, but if the nine major earthquake epicenters recorded by Milne, mapped by Reeds, and recently discussed by the writer * mean what they seem to mean they suggest strongly a new or incipient arc of the Coast Range now forming on the ocean floor. Another line of epicenters runs south to the Marshall Islands about on the west limb of the new arc produced. In the Malay earthlobe, the Andaman-Java-Ceram arc appears to correspond to our Coast Range. According to Suess, the main Himalaya range stands as Number 1 in front of the Andaman-Java arc which, as Number 2, laps around the east end of the Himalayas, in which case the Mentavi-Timor arc may also be part of Number 1. It seems probable, therefore, that the main range of the Himalayas and the Mentavi-Timor arc are younger than the Coast Range in North America.

Since the whole Tertiary Mountain belt of the earth is substantially a unit in diastrophism, it seems fairly safe to correlate the most northerly of the Tertiary ranges—the Hindu Kush, Caucasus, Carpathians, Swiss Alps, and Pyrenees—with the Rocky Mountains of North America. South of Japan, the Marianas-Pelew arc is evidently later than the Cascade Range, but older than the Coast Range.

The case for Australia seems simple. The mountains of the eastern border seem to correlate with our Rockies—an older range rejuvenated in the late Cretaceous and early Tertiary. The arc of New Guinea, New Caledonia, and New Zealand appears clearly to be of Cascadian age, while the arc of the

* Bull. Geol. Soc. Am., vol. 39, 1928.

Solomon Islands, the New Hebrides, etcetera, is intermediate, like the Marianas-Pelew arc in the northern hemisphere. Finally, island lines running southeast and east from the Marshall Islands may possibly correspond to the incipient Coast Range arc in the northern Pacific.

South America, Middle America, and the West Indies appear to present the most difficult problems. The West Indies appear to belong structurally mainly to South America, Middle America mainly to North America. The Andes, like the Alps in Europe, appear to combine in one range, or in several very closely appressed ranges, the three Tertiary diastrophic episodes seen in North America.

The correlations here suggested are based mainly on the physical continuity of the ranges, as of the Rocky to the Stanovoi Mountains, and of the Cascade Range through the Aleutian arc to the other festoon arcs of eastern Asia. In other cases some dependence is placed on the principle of corresponding order in similar series, as when Australia is compared to eastern Asia. If these correlations are sound they show genetic relationships and a systematic plan in the whole Tertiary Mountain system of the earth.

Read by title in the absence of the author.

NEW CLASSIFICATION OF THE PALEOZOIC DEPOSITS IN OKLAHOMA

BY E. O. ULRICH

(*Abstract*)

In 1903 and 1904 Joseph A. Taff described and mapped the rocks exposed in and about the Arbuckle and Wichita Mountains in Oklahoma. The pre-Mississippian marine deposits, with which this paper is mainly concerned, he divided into six formations, as follows: (1) the Reagan sandstone, then supposed to be of Middle Cambrian age, at the base; (2) the Arbuckle limestone, 5,000 feet in thickness and thought to represent a record of limestone deposition, beginning with the Upper Cambrian and extending well into the Ordovician; (3) the Simpson formation, an alternating but variable series of sandstone, shales, and limestones of Middle Ordovician age: (4) the Viola limestone of Upper Ordovician age; (5) the Sylvan shale assigned to the base of the Silurian; and (6) the Hunton formation, the even then known Silurian to Lower and Middle Devonian members of which were subsequently separated under distinct names by Reeds. Above the Hunton is the Woodford chert, consisting of more or less cherty black shale then assigned to the Upper Devonian, but now referred to the base of the Mississippian system.

Study of collections of fossils and sections made during the course of Taff's work in the area and renewed field and office studies carried on at intervals during the past five years and more continuously during the latter half of this period, with the welcome collaboration of Prof. C. E. Decker, soon indicated and finally proved the inadequacy of the original classification of the concerned pre-Mississippian deposits. Of the mentioned seven formation names only the Reagan sandstone, the Sylvan shale, and the Woodford chert or shale can be maintained in the sense in which they were used by Taff. The Arbuckle limestone, which was found to comprise a number of

readily distinguishable and variously distributed stratigraphic units, having an aggregate thickness of nearly 10,000 feet, is divided into nine and perhaps ten distinct formations. Two of these are of Upper Cambrian, five or six of Ozarkian, and three of Canadian age. The Simpson formation, also, is divided into six formations. Each of these new stratigraphic units has its own distinctive fauna, diastrophic history, areal distribution, and paleogeographic relations.

WIDESPREAD MAPPING OF THE AFTONIAN AND YARMOUTH INTERGLACIAL HORIZONS IN IOWA

BY GEORGE F. KAY

(*Abstract*)

For more than ten years members of the Iowa Geological Survey have been mapping the outcrops of Nebraskan and Kansan gumbotils in Iowa. These gumbotils, because of their distinctive characters, topographic positions, and wide distribution, have proved to be the most satisfactory Aftonian and Yarmouth interglacial horizon markers in the State. They have been especially useful in differentiating and mapping the two oldest tills.

Peats and weathered gravels have been and will continue to be of value in interpreting interglacial history, but they have been found to be less serviceable than the gumbotils in areal mapping in Iowa. Only a few good exposures of peat of Aftonian age have been found in the whole State, and these are separated widely from one another. Nor are there many good exposures of peat of Yarmouth age. Moreover, since gravels differ in origin, in topographic position, in degree of weathering, and in other respects, their use in mapping is somewhat restricted. Much less reliance is now placed upon interpretations of gravels and "forest beds" penetrated in well drillings than was given to these materials in the earlier years of Pleistocene studies.

Two maps have been prepared. One of these maps shows the locations of outcrops of Nebraskan gumbotil of Aftonian age, separating Nebraskan till from Kansan till in Iowa, and the other map shows locations of outcrops of Kansan gumbotil of Yarmouth age. The former map reveals clearly that the Nebraskan gumbotil is widespread in southwestern Iowa; in fact, from these gumbotil outcrops it is now possible to map areally the Nebraskan drift of this region. This map shows also that Nebraskan gumbotil extends into the northwestern part of the State, and that comparatively few outcrops of this gumbotil have been found within the Iowan area of northeastern Iowa or in southeastern Iowa.

Within the Iowan area of northeastern Iowa, not only are there few known exposures of Nebraskan gumbotil, which represents the Aftonian horizon, but exposures of Aftonian peats and gravels are rare. On the contrary, within this Iowan area there are many exposures of Kansan gumbotil, which represents the Yarmouth interglacial horizon. At the surface of several of the Kansan gumbotil exposures within the Iowan area there is a distinct soil zone, or "forest bed," above which there is calcareous Iowan drift. Furthermore, at the same topographic position as the Kansan gumbotil, there are in many places thoroughly leached gravels—the upland phase of the Buchanan

gravels of Calvin—overlying which in many places there is thin Iowan drift. From these facts it is now possible to state that within the area of Iowan drift in northeastern Iowa (the area mapped by McGee), the Kansan gumbotil (McGee's gumbo, which he stated was the stratigraphic equivalent of his forest bed) is much better known from observation than the Nebraskan gumbotil, or peat separating the Nebraskan till from the Kansan till. In other words, the "forest bed horizon" has been mapped more widely between the Kansan till and Iowan till—that is, between the tills which McGee mapped areally as his lower and upper tills—than between the Nebraskan and Kansan tills in this part of the State. It is believed that the Nebraskan gumbotil is at the horizon of the forest bed on Winchell's "older" till of southeastern Minnesota, and that the Kansan gumbotil is at the surface of his "old" till in the same area. McGee's upper till in Iowa, the Iowan, was apparently not differentiated in Minnesota by Winchell, although it is present there. Nor did McGee map in Iowa Winchell's "older" till.

Both Winchell and McGee had an upper till and a lower till. It is believed that Winchell's upper till, or "old" till, is the present Kansan till, and that his lower till, or "older" till, is the present Nebraskan till. McGee's upper till is the present Iowan till and his lower till is the present Kansan till. Together they recognized the three tills which are now known as the Nebraskan, the Kansan, and the Iowan tills. Both of them were familiar also with Winchell's "younger" till, which is the present Wisconsin till.

The absence of Kansan gumbotil in northwestern Iowa has been explained to be the result of erosion of this gumbotil after it had been developed on Kansan till here as well as in other parts of the State.

The Kansan gumbotil has been found in many places beneath the Illinoian till of southeastern Iowa, and in a few places within the Illinoian drift area Nebraskan gumbotil has been found beneath the Kansan till.

The mapping of the outcrops of Nebraskan gumbotil and Kansan gumbotil has impressed the fact that the original Nebraskan gumbotil plain and the original Kansan gumbotil plain are widespread in the State. It is somewhat surprising to find that so much of each of these plains has escaped erosion. Remnants of the Kansan gumbotil plain are a striking feature of the topography of the Kansan drift area of southern Iowa, where they are known as tabular divides.

Brief remarks were made by Messrs. Frank Leverett, Bailey Willis, and M. M. Leighton.

At this point, 1 p. m., the session adjourned for luncheon.

Session of Thursday Afternoon

The afternoon session was occupied with a special symposium on the centenary of the glacial theory, in joint session with Section E of the American Association for the Advancement of Science, Prof. Henry Fair-

field Osborn acting as chairman and Prof. Frank Leverett as vice-chairman. This session was held in the Auditorium of the American Museum of Natural History. For a full account of the program refer to Proceedings of Section E (see pages 199-204 of this Bulletin).

SECTIONAL MEETING IN DUPLEX ASSEMBLY ROOM, SCHOOL SERVICE BUILDING

The meeting was called to order at 2 p. m., Vice-President Alfred C. Lane acting as chairman.

TITLES AND ABSTRACTS OF PAPERS

FAULT-BLOCK OF CAMBRIAN STRATA IN NORTHERN ILLINOIS[1]

BY ARTHUR BEVAN

(*Abstract*)

The area discussed is a small one near Oregon, in Rock Valley, about 90 miles west of Chicago. It contains the oldest exposed formation in the State and shows the most complex structure yet discovered in northern Illinois.

The formations hitherto known to crop out in this part of the State are of Ordovician age. The New Richmond sandstone, in the middle part of the Prairie du Chien Series (Lower Ordovician), has been considered as the oldest exposed formation in the State. It has long been known that the prevailing gentle regional dips are interrupted by the northwesterly axis of the prominent La Salle anticline, and that this anticline is intersected at Oregon by an east-west anticline.

Detailed study of the Oregon Quadrangle for the Illinois State Geological Survey has resulted in the discovery of a small area of exposed strata which seem to be Upper Cambrian. The section to be discussed consists of (1) a thick white sandstone below, (2) a conspicuous glauconitic sandstone, (3) a limestone, and (4) Saint Peter sandstone, with a prominent breccia in its lower portion. This section is compared with the known Cambro-Ordovician section of the general region, and it is interpreted as Dresbach sandstone below, followed by the Mazomanie formation, on which the Saint Peter sandstone lies with marked disconformity.

The presence of this Cambrian inlier in the broad expanse of Ordovician formations has been caused by faults. The low ridge on the broad floor of Rock Valley is composed entirely of the above-named formations. This ridge is a wedge-shaped block bounded by a pair of faults, or fault zones, which trend northwest-southeast. Saint Peter sandstone crops out on both sides of this block. Further evidence of the faults consists in stratigraphic offsets, duplication of strata, and the prominent fault breccia. At least one fault is of the thrust type.

The exceptional deformation of this area appears to be related to the intersection at a high angle of the two anticlines at Oregon.

[1] Published by permission of the Chief, Illinois State Geological Survey.

STRUCTURE AND STRATIGRAPHY AT THE JUNCTION OF THE WASATCH MOUNTAINS WITH THE WASATCH PLATEAU

BY HYRUM SCHNEIDER

(*Abstract*)

The area to be discussed is on the border of the high plateaus and the Great Basin, two important physiographic provinces that differ from each other in their geology as well as in their physiography. The section is traversed by the Denver and Rio Grande Railroad and by a transcontinental automobile road. Thistle Junction, Utah, a station on the Denver and Rio Grande Railroad, is on the west margin of the area mapped.

A thick Cretaceous conglomerate previously mapped as Tertiary suggests that there may have been some physiographic disturbances in this region before the Upper Cretaceous rocks were deposited. The thick conglomerate and the overlying lower Colorado sandstone represent a west shore phase of the Cretaceous not previously described.

The relation of the Tertiary to the Cretaceous rocks indicates that the lake in which the Tertiary rocks were deposited had an uneven bottom and an abrupt and irregular west shoreline. Some time after the sediments of the Green River formation were deposited, the Tertiary rocks were compressed into an anticlinal fold which is roughly parallel to the strike of the rocks that were folded during the Laramide orogeny.

In the Tertiary rocks there is a petroliferous horizon which appears to have derived its petroleum from gasteropods. The petroliferous rocks are in close association with beds rich in gasteropods, and in a few cases petroliferous gasteropod nuclei were found in non-petroliferous concretions.

Brief remarks were made by Messrs. W. C. Mansfield and Peters.

STRUCTURAL MAPPING OF THE KNIFE LAKE SLATES OF MINNESOTA

BY JOHN W. GRUNER

(*Abstract*)

A beginning has been made in deciphering the highly folded structures of the Huronian slates and graywackes along the international border in northern Minnesota. On account of the burned-over conditions of the area, it was possible to map the structures with a very much greater accuracy than is usual in Precambrian folds.

The stratigraphic thickness of the beds in the area so far mapped is about 2,500 feet. Tuffs and slates predominate. Graywackes and conglomerates are subordinate. Narrow bands of iron formation occur in many places.

The folds are nearly isoclinal and close to vertical. Their general strikes are north 40 degrees to 60 degrees east. Their pitch varies between 10 and 60 degrees to the northeast.

In the working out of the structure the criteria in the order of importance are: (1) horizon markers, (2) gradational bedding, (3) dragfolds. Cross-bedding is almost absent. Ripple-marks were not seen at all. For horizon markers may be used: (*a*) bands of jaspery iron formation, (*b*) agglomer-

ates in the tuffs resembling thin conglomerates, (*c*) tuff layers weathering with holes resembling amygdaloidal cavities, (*d*) conglomerates, (*e*) massive tuff layers upward of 20 feet in thickness. They resemble porphyries containing hornblende phenocrysts.

Zones where carbonates and quartz have replaced the tuffs and slates cut across all the other structures.

NEW GEOLOGIC MAP OF VIRGINIA

BY WILBUR A. NELSON

(*Abstract*)

The recent geologic map of Virginia, prepared under the direction of George W. Stose, Geologic Map Editor of the U. S. Geological Survey, and published by Virginia Geological Survey, shows by cartographic representation new and little known geologic features of Virginia.

It is unique in representing for the first time certain stratigraphic and structural features, chief of which are the classification of the Precambrian and the major structural features of the State in the region lying between the Blue Ridge and the Coastal Plain, by Miss Anna I. Jonas and others; the refinement of mapping and divisions of the Coastal Plain showing the great overlapping in the Tertiary toward the south, by W. C. Mansfield and others; the refinement of mapping of the Paleozoic formations in the valley region of Virginia, west of the Blue Ridge, showing group relations, basins, hiatuses, structural features, and reproduction in remarkable detail of the principal divisions of the Carboniferous, by Charles Butts and others.

Brief remarks were made by Prof. John S. Grasty.

STRUCTURE OF THE METAMORPHIC BELT OF THE CENTRAL APPALACHIANS

BY ANNA I. JONAS

(*Abstract*)

The metamorphic folded belt of the Appalachians in the area from eastern Pennsylvania to North Carolina consists of a southeastern or Martic overthrust block lying west of the Coastal Plain sediments and, on the west, the anticlinal uplifts and synclinal infolds of the Highland-Blue Ridge geanticline, bounded on the west by the Great Valley.

Both divisions are made up of closely folded rocks of Precambrian and Paleozoic age that are broken by thrust-faults, showing all gradations from broken recumbent anticlines to clean-cut thrusts developed from them and low-angle thrusts of the Scottish Highland type. The thrusts of the geanticline belong to the former, while the Martic thrust belongs to the latter class. It bounds a block of the earth's crust whose eastern part is covered by Coastal Plain sediments. Its linear extent has been traced from the edge of these sediments in eastern Pennsylvania southwest into North Carolina.

The great width of the Martic overthrust block in southern Virginia is in part due to the southeast curve of Coastal Plain sediments and to the southwest direction of normal Triassic faults that form its northwestern border

throughout most of Virginia, as well as the westward advance of the overthrust mass. The southwest direction of Triassic faults transverse to the folds of the geanticline on the uplifted side of the normal faults have had the effect of cutting them off from east to west and of decreasing the width of this belt.

The Martic overthrust is of post-Ordovician age and may be post-Mississippian, corresponding in age to the thrusts in and west of the geanticline. It is cut south of Baltimore by little deformed granites intruded after the last folding that affected the thrust-block, but no similar granites are exposed in the geanticline northeast of northern North Carolina.

Read by title in the absence of the author.

THERMAL SPRINGS OF VIRGINIA

BY FRANK REEVES

(*Abstract*)

In the northwestern part of Virginia and adjacent parts of West Virginia there are ninety springs which are classed as thermal springs in the sense that they have temperatures distinctly above the mean annual air temperature. The temperature of these springs ranges from 55 to 105 degrees Fahrenheit. The waters are calcium carbonate or calcium sulphate water, or a mixture of the two. The mineral content of most of the springs ranges from 100 to 600 parts per million. The gases escaping from the springs have the following average composition: nitrogen, 86.5 per cent; oxygen, 8.5 per cent, and carbon dioxide, 5 per cent. In mineral composition and gas content the thermal springs are similar to the cold springs, the only difference being that the warmer of the thermal springs have a slightly greater mineral content and a higher per cent of sulphates than most of the cold springs.

Approximately all of the thermal springs issue either from Ordovicion limestones or from the Oriskany sandstone of Devonian age, where these strata rise to the surface from considerable depths because of anticlinal folding, or, in rare instances, because of thrust-faulting. They invariably issue only at the lowest exposure, topographically, of these rocks in the different anticlines or overthrust faults. They are therefore commonly found in water gaps and in the valleys of large streams. In anticlines where the water-bearing formations are not exposed at as low a level as in adjacent anticlines, only cold springs are found. The temperatures of the thermal springs are commonly proportionate to the depth that the water-bearing formations are buried in synclinal areas adjacent to the springs, the temperatures apparently never exceeding the earth temperatures attained by those rocks in the synclinal basins.

The hypothesis as to the origin of the heat and water supply of the thermal springs which is the most consistent with the facts of their chemical composition and geologic occurrence is that they are due to the artesian circulation of meteoric water. The water evidently enters a permeable bed at its outcrop in a relatively high anticlinal valley and rises to the surface at its outcrop at a lower point in an adjacent anticline, attaining in the intervening synclinal basin through which it passes the rock temperature normal to

the earth at those depths. The condition, therefore, for the occurrence of thermal springs of this type is a highly folded terrain with considerable relief, containing beds sufficiently permeable to act as aquifers, the continuity of which is not broken by faulting.

GEOLOGY OF FLORIDA

BY C. WYTHE COOKE AND STUART MOSSOM

(*Abstract*)

The "Geology of Florida," which will form part of the Twentieth Annual Report of the Florida Geological Survey, includes a new map of the State (exhibited).

Florida is underlain by Paleozoic or older metamorphic rocks which may be the continuation beneath the Coastal Plain of the rocks of the Piedmont region of Georgia. They probably lie closest to the surface in the Ocala uplift, where mica schist and quartzite were encountered below 4,100 feet.

Limestone and shale containing Upper Cretaceous fossils have been penetrated by several deep wells, but they do not crop out anywhere in Florida. The oldest rock exposed in Florida is upper Eocene Ocala limestone, which underlies the entire State and occupies many hundreds of square miles of its surface.

Oligocene rocks are represented by the Marianna limestone, the Glendon limestone, and the Byram marl, comprising the Vicksburg group.

The writers have revived the name "Hawthorn formation," which was abandoned in 1914, and have added it to the Miocene Alum Bluff group. They have tentatively included the "Jacksonville formation" in the Hawthorn because they found it impracticable to map it separately. Three faunal zones are established in the upper Miocene Choctawhatchee formation on the authority of W. C. Mansfield.

The name "Nashua marl," used in former reports for marine Pliocene shell marl on the East Coast, is abandoned and the deposits to which it was applied are included in the Caloosahatchee marl with which they are contemporaneous. The sands and gravels of the Citronelle formation are correlated with similar materials in the Peninsula. The Alachua formation, which contains the hard-rock phosphate deposits, is regarded as in large part residual from phosphatic limestone of the Hawthorn formation. The contemporaneous Bone Valley gravel, noted for its land-pebble phosphate, may be partly residual and partly alluvial. Both the Alachua and the Bone Valley contain Pliocene vertebrates. The Charlton formation is questionably of Pliocene age.

The marine Pleistocene formations fringe the coast and seem to be contemporaneous. From north to south occur the Anastasia formation (including the "Palm Beach limestone"), the Miami oolite (including the "Key West" oolite), and the Key Largo limestone. The names "Palm Beach limestone" and "Key West oolite" are not retained. A new name, the Melbourne bone bed, is proposed for the deposits at Melbourne, Vero, and elsewhere that enclose *in situ* remains of many extinct land animals and from which human bones have been reported.

Brief remarks were made by Prof. Andrew C. Lawson.

DEVONO-MISSISSIPPIAN BOUNDARY IN VIRGINIA AND TENNESSEE

BY JOEL H. SWARTZ

(*Abstract*)

In 1927 the Chattanooga shale was shown by the writer to be entirely Mississippian in age in the type area and largely so in the rest of northeastern Tennessee and southwestern Virginia, where it is underlain by beds of Portage facies. In the past the Chemung was thought to be missing, and the Devonian and Mississippian therefore separated by a considerable hiatus. Recent work by the writer proves that:

1. The Chemung is *not* missing from this area. It passes laterally along the strike into beds of Portage facies which are equivalent to the more normal Chemung of the Saltville region.

2. The Portage (in part), the Chemung, and the Chattanooga all merge at the southern end of Clinch Mountain into a single black shale series. The same lithology and environment are found on both sides of any break which may be present.

3. The southward overlap of the Upper Devonian is continued through lower and middle Chattanoogan time. There is no withdrawal, noticeable break, or change in the transgression of the sea as it passes from beds with a Chemung fauna to beds with a Cuyahogan fauna.

The presence of the Chemung, the identical environments on both sides of the boundary, and the continued transgression of the sea across the boundary all show that any break between the Devonian and the Mississippian must be slight.

4. The lower part of the Cumberland Gap member of the Chattanooga shale in its northern exposures is Chemung in age, the Devono-Mississippian boundary lying within this member; but the writer could not separate the Devonian from the Mississippian portion of the Cumberland Gap member except in the area just south of Kermit, Virginia. If such differentiation becomes practicable, the Devonian portion of the member should be removed as a separate formation and the name "Chattanoogan" restricted to the Mississippian part, since that part alone is developed at Chattanooga.

Brief remarks were made by Dr. E. O. Ulrich.

ADDRESS OF THE RETIRING PRESIDENT OF THE MINERALOGICAL SOCIETY

At 4 o'clock the joint session arranged with the Mineralogical Society was called, Vice-President Esper S. Larsen, Jr., retiring President of the Mineralogical Society of America, taking charge of the session and presenting an address entitled "Temperature of magmas."[1]

At the conclusion of this address the additional papers listed for the joint session were presented.

[1] This paper will be published in the current volume of The American Mineralogist.

TITLES AND ABSTRACTS OF PAPERS

DURATION OF PEGMATITE CRYSTALLIZATION

BY ALFRED C. LANE

(Abstract)

In connection with Kirsch's theory that the Broeggerite crystals vary in age something like 200 million years, occurring at intervals of something like 35 million years, as developed in his new book "Radioaktivität und Geologie," the derivation of pegmatite crystallization will be brought up for discussion.

The less the difference in conditions between the injected magma and the environmental country rock, the longer the time in the labile zone and according to the author's theory, the latest statement of which is to be found in Fairbanks' "Laboratory Investigation of Ores," the coarser will be the grain.

This passage through the labile zone is particularly slow when the conditions of the country rock are close to those of the labile zone of crystallization. It was obviously slow in the pegmatites, and then slight changes in country rock conditions might profoundly affect crystallization.

Brief remarks were made by Mr. Frank L. Hess.

AUTHIGENIC FELDSPAR IN LIMESTONE AT GLENS FALLS, NEW YORK

BY JOSEPH T. SINGEWALD, JR., AND CHARLES MILTON

(Abstract)

On both sides of the Hudson River at Glens Falls, New York, is a series of small limestone quarries that have produced stone for lime burning from 15 feet of pure limestone. The rock is a fine-grained dark to nearly black limestone of Trenton age.

Microscopic examination revealed feldspar to be an abundant constituent of the insoluble residue which contained much smaller amounts of garnet, rutile, zircon, and a few grains of tourmaline, titanite, staurolite, hornblende, and barite. The feldspar occurs in euhedral crystals showing the usual basal and side pinacoids, unit pyramids, and prisms, and elongation parallel to the *a* axis. Ramifying aggregates of many individuals occur. These characteristics prove the authigenic origin of the feldspar.

Chemical analysis and microphotographs of the feldspar are given.

MELTING GRANITE AND BASALT IN THE LABORATORY

BY J. W. GREIG, E. S. SHEPHERD, AND H. E. MERWIN

(Abstract)

It is held by many that experiments on the melting of granites and basalts have shown a higher melting temperature for granites than for basalts under laboratory conditions. Studies of equilibrium in silicate systems have indicated the reverse. Moreover, consideration of those earlier experiments in the light of our present knowledge shows that they were inadequate to decide the question. Since a laboratory determination of the temperature of complete melting for specimens of granite and of basalt and diabase may carry

more conviction than discussions of the question based on studies of equilibrium in simpler silicate systems, such a determination has been carried out. The results show conclusively that under laboratory conditions granite melts at considerably lower temperatures than basalt or diabase. In the typical specimens used the difference amounts to over 200 degrees centigrade.

Brief remarks were made by Dr. N. L. Bowen.

AGES AND DIFFERENTIATION SERIES OF BATHOLITHS NEAR THE MINNESOTA-ONTARIO BOUNDARY

BY FRANK F. GROUT

(*Abstract*)

The first part of this paper shows the complexity of the periods of batholithic invasion northwest of Lake Superior. The evidence is fairly strong that there were two epochs of Laurentian invasion, two epochs of Algomian invasion, and a probable Keweenawan invasion; a total of five events in at least three great intervals. In this distribution through several epochs they resemble the Appalachian and Cordilleran batholiths.

The early batholiths of a period are rendered gneissic if any later batholiths are injected near them. The latest batholith in any district is likely to be little altered, whether Laurentian, or Algomian, or later.

The second part summarizes the petrographic and chemical characters of the batholiths of well determined age relations. This part of the results is largely negative. The differentiation series in one epoch is much like that in another. There are few, if any, petrographic criteria which could be safely applied to distinguish batholiths of different ages. Certain differences are noted, to be sure, but there is no feature that seems likely to be at all general in its application, even in a region as restricted as the Lake Superior region. There is more variation inside of one batholith than between the average Laurentian and Algomian masses.

Brief remarks were made by Messrs. Andrew C. Lawson, Alfred C. Lane, Arthur Keith, and Esper S. Larsen, Jr.

CHRYSOTILE VEINS OF SOUTHERN QUEBEC

BY STEPHEN TABER

(*Abstract*)

In a study of the asbestos deposits of southern Quebec additional evidence was obtained in support of Graham's theory that serpentinization of the peridotites was due to siliceous waters of magmatic origin. The serpentine is cut by dikes and lenses of granite, aplite, and pegmatite. Pectolite and prehnite, occurring in vugs in the granite, have not been mentioned in previous descriptions of the district.

In places, chrysotile veins extend for short distances into the granite. Some of this chrysotile is similar to the chrysotile in the serpentine, but some of it differs in physical properties and probably in chemical composition. Some

of the veins in the granite contain columnar quartz that appears to have been deposited simultaneously with the chrysotile. This unusual occurrence of chrysotile, together with evidence obtained from vein intersections and from a study of small faults contemporaneous in origin with the veins, all furnish additional support for the theory that the wall rock in immediate contact with the veins has been displaced as the veins were formed instead of being destroyed by replacement or recrystallization.

Read by title.

At the conclusion of this program the session was adjourned, at approximately 6 p. m.

Session of Friday Morning, December 28

The session was called to order at 9:20 o'clock by President Willis, in the Duplex Assembly Room, School Service Building, American Museum of Natural History, and the scientific papers listed on the official program were taken up at once, the first one called being by Frederick J. Pack, entitled "Origin of the erosional forms at Bryce Canyon National Park."

At this point the business scheduled for the morning session was presented, the principal item being the resolution adopted by the Council relating to incorporation of the Society. After preliminary explanation by the President, the Secretary gave a brief review of the steps that have been taken in studying the question of incorporation and the stage now reached in the program mapped out by the Special Finance Committee with the approval of the Council. The latest action was a canvass of the entire fellowship of the Society on the question of incorporation, which resulted in overwhelming approval.

The following resolution was then presented:

Resolution on Incorporation of the Geological Society of America

Recommended by the Council

Whereas a Special Finance Committee was appointed by the President to study the financial structure of the Society and recommended that such steps as may be necessary should be taken to incorporate the Society; and

Whereas the Council, pursuant to the provisions of the Constitution of the Society, submitted in print to all Fellows, under date of September 28, 1928 (said date being three months previous to the date of this meeting), a proposal to incorporate this Society, and stated in said proposal that the Society would be called upon at the annual meeting to elect a committee of at least five to accomplish incorporation, in the event that at least three-quarters of all the Fellows voted in favor of the said proposal to incorporate the Society; and

Whereas votes in favor of the incorporation of the Society have been received from more than three-quarters of all the Fellows, namely, from 439 Fellows out of a total of 536 Fellows; and

Whereas it is deemed advisable by the Council that the Society should be incorporated under the provisions of the Memberships Corporation Law of the State of New York; and

Whereas it is provided in the said law that any unincorporated association, society, league, or club not organized for pecuniary profit may be incorporated under the said law, provided that the subscribers of the certificate of incorporation constitute a majority of the members of a committee consisting of at least five persons, which committee has been authorized to incorporate such association, society, league, or club by vote, as required by the organic law of the association, society, league, or club, for the amendment of such organic law; and

Whereas all the conditions hereinabove set forth contained in the laws of the State of New York as conditions precedent to the incorporation of this Society have been complied with, it is now, on motion, duly made and seconded, unanimously

Resolved, That Charles P. Berkey (chairman), Heinrich Ries, H. Foster Bain, Joseph Stanley-Brown, and Henry Fairfield Osborn be, and they hereby, are authorized to incorporate the Geological Society of America, an existing unincorporated society not organized for pecuniary profit, pursuant to the provisions of Memberships Corporation Law of the State of New York, for the purposes for which it was organized; which said purposes are purposes for which a corporation may be formed under the Memberships Corporation Law of the State of New York, and to take any and all such steps as may be provided for by law or may be advisable or necessary to complete the said incorporation, including the execution of the certificate of incorporation of the Society and any and all other documents which may be necessary or requisite.

At the conclusion of the reading of this resolution it was duly moved and seconded that it be approved and adopted, and it was carried unanimously, without discussion.

REPORT OF THE AUDITING COMMITTEE

To the Geological Society of America:

Your Auditing Committee has examined the accounts of the Treasurer and finds them to be correct, and that the securities of the Society deposited with the Baltimore Trust Company check with the record as presented by the Treasurer.

G. F. KAY, *Chairman*,
LEWIS G. WESTGATE,
E. W. BERRY,
Auditing Committee.

This report was received and accepted, conditioned on receipt of an additional section of the report covering the securities.

REPORT ON SECURITIES OWNED BY GEOLOGICAL SOCIETY

The following list of securities were verified by Professor Berry, as shown by the letter attached herewith:

5,000 City of Philadelphia 4 per cent loan of October 1, 1920, 1953.
1,000 Iowa Apartment House Company stock.
4,000 Ontario Apartment House Company stock.
2,000 Texas and Pacific Railway Company first mortgage 5 per cent, 1950.
2,000 United States Steel Corporation second mortgage 5 per cent, 1963.
2,000 Fairmont and Clarksburg Traction Company first mortgage 5 per cent, 1938.
2,000 Consolidation Coal Company first and refunding mortgage 40-year sinking fund gold 5 per cent, 1950.
3,000 Chicago Railways first mortgage 5 per cent.
2,000 Southern Bell Telephone and Telegraph Company first mortgage 5 per cent, 1941.
2,000 American Telephone and Telegraph Company 20-year sinking fund 5½ per cent gold debenture, 1943.
1,000 Louisville and Nashville Railroad Company 10-year 7 per cent gold note, 1930.
1,000 Commonwealth Edison first mortgage gold 5 per cent, 1943.
2,000 Commonwealth Edison first collateral trust 5 per cent, 1954.
2,000 Anaconda Copper Mining Company first mortgage 6 per cent, 1953.
2,000 Baltimore and Ohio Railroad Company first mortgage 5 per cent, 1948.
2,000 Central Railways of Baltimore first mortgage 5 per cent, 1948.
2,000 Canadian Pacific Railway Company 20-year 4½ per cent, 1946.
2,000 Westinghouse Electric and Manufacturing Company 5 per cent, 1946.
2,000 Bethlehem Steel Corporation 6 per cent, 1948.
2,000 Southern Pacific Railway Company 40-year 4½ per cent, 1968.
2,000 Shawinigan Water and Power Company first mortgage A bonds, 1967.

DEAR DR. BERKEY:

As one of the auditors appointed at the annual meeting of the Geological Society of America, I have today examined and checked the securities of the Society deposited with the Baltimore Trust Company and found them to correspond with the list submitted by the Treasurer and enclosed herewith.

Very truly yours,

EDWARD W. BERRY.

January 21, 1929.

TITLES AND ABSTRACTS OF PAPERS

ORIGIN OF THE EROSIONAL FORMS AT BRYCE CANYON, NATIONAL PARK

BY FREDERICK J. PACK

(*Abstract*)

Bryce Canyon, really an amphitheater, is situated at the east rim of the Paunsaugunt plateau, the face of which is receding at a somewhat accurately measurable rate. Literally thousands of fantastic erosional forms are left in the path of the recession. Differential attack by frost, made possible by differential distribution of run-off, is chiefly responsible for the origin of these forms. Differential resistance plays a supplementary part.

Brief remarks were made by Prof. Harry N. Eaton.

FEATURES OF GYPSUM-ANHYDRITE SALT DOME CAP ROCK

BY MARCUS I. GOLDMAN

(*Abstract*)

Two features of the cap rock will be discussed. One is the effect of tectonic disturbance on the rock, the other is the relation of gypsum and anhydrite to each other and to depth.

The anhydrite cap rock originates by solution of the top of the underlying salt plug with consequent accumulation of the less soluble anhydrite beds contained in the salt. This is proved by the presence in the cap rock of fragments of a fine-grained white anhydrite rock with black stratification lines regarded as evidence of primary sedimentary origin. Between these fragments is a matrix of coarser, generally darker anhydrite crystallized from solution. Presumably by the upward movement of the salt plug this mass of anhydrite fragments has been subjected to intense pressure, resulting in most complex folding and flowage of the rock. This flowage is interesting on account of its resemblance to similar phenomena in gneisses and schists. It seems to have taken place by crushing of part of the rock to a very fine meal which acted as a matrix in which the uncrushed crystals of anhydrite were carried along and some of them bent and broken. This process, together with crystallographic reintegration of the crushed parts, helps to explain the surprising preservation of structure in sedimentary rocks, especially limestones, which have undergone flowage.

In a later stage the cap rock has developed nearly horizontal shear surfaces and nearly vertical fissures. Along these two lines of weakness gypsification has commenced. The shear surfaces are much more common than the vertical fissures. Both are probably results of yielding to bending stresses due to the upward thrust of the salt plug. Accordingly the vertical fissures are almost restricted to the upper part of the cap. Movement on any single shear surface has apparently been very slight.

A depth relation of gypsum and anhydrite is generally recognized. Gypsum apparently forms in the upper part of anhydrite bodies, though the reverse

process, so far as the author knows, has never been recorded. In this cap rock, also, gypsum characterizes the upper part of the mass of calcium sulphate, but near faults in depth gypsum forms abundantly in the anhydrite zone. This gypsum, however, goes back in part to anhydrite, which can in some cases be identified by peculiarities of its habit.

GEOMORPHIC VALUE OF RIVER GRAVELS

BY MARIUS R. CAMPBELL

(*Abstract*)

Heretofore little, if any, attention has been given to river gravel as a possible means of determining the stage of the cycle of erosion in which it was deposited, and also of determining recent crustal movements. The writer believes that, in many cases, both are possible. The paper presents a study of the conditions which lead to the formation of deposits of stream gravel in various stages of the cycle of erosion. The subject is treated under three heads: (1) supply of hard-rock material; (2) transportation and abrasion of this material, and (3) deposition of the rounded material in the form of pebbles, cobbles, or boulders. The conclusion is that, in the post-mature stage of the cycle, this material will generally be deposited in such situations that enough will be preserved, even after the drainage system has been rejuvenated, to enable the geomorphologist to trace and correlate the gravel from point to point along the course of the stream. Such a nearly continuous bed of gravel not only indicates a post-mature stage of erosion, but it affords, by the small gradient which it implies, a means of determining any small crustal movement that may have occurred at a later date.

Brief remarks were made by Dr. Florence Bascom, and by Messrs. Andrew C. Lawson, Frank Leverett, and George W. Stose.

GRANITE PHACOLITHS AND THEIR CONTACT ZONES IN THE NORTHWEST ADIRONDACKS

BY A. F. BUDDINGTON

(*Abstract*)

In the foothill belt of the northwest Adirondack province, lying southeast of the Saint Lawrence River and parallel to it, there is a belt of Grenville formations, with associated intrusive igneous rocks, exposed for a length of 60 miles and a width of 30 miles. In this belt 14 elongate granite masses, from 2 to over 15 miles in length, have been studied by the writer, and are interpreted as phacoliths resulting from intrusion of magma in the crests of anticlinal folds and subsequent intense deformation by continued folding before the magma completely consolidated. This interpretation is based on the restriction of the granite bodies to anticlinal folds; on the general conformity between the borders of the granite mass and the bedding of the country rock, both on the limbs and on the plunging noses of folds; on the common occurrence of domical foliation and the actual exposure of the base of a major phacolith; and upon contemporaneity of folding and intrusion, as indicated by phenomena connected with the foliation

and texture of crystallization. The enclosing folds of the Grenville are isoclinal and either vertical or overturned, with a uniform homoclinal dip as low as 30 degrees northwest and a pitch from 30 to 70 degrees northeast or southwest.

A porphyritic type of granite has the structural relations of intrusive sheets and there are some indications that it may be slightly older than the granite phacoliths and may have been folded along with the enclosing Grenville beds, as have a series of older gabbro, diorite, quartz diorite, and monzonite sills and phacoliths.

The structure of the northwest Adirondacks is interpreted as essentially the result of the complex interplay of thrusts due to magmatic intrusion and of deformation by an orogenic pressure acting along northwest-southeast lines. A minor component acting along northeast-southwest lines has produced corresponding structures at right angles. The pressure exerted by the magma is in turn believed to arise from the orogenic forces.

Along much of the contact between the granite masses and the limestone country rock there is a narrow zone up to 150 feet in width that consists of hornblende or pyroxene gneiss, intrusive sills of granite, sheets of garnet-sillimanite gneiss, and dikes and lenses of pegmatite. The hornblende and pyroxene gneiss layers are interpreted as limestone layers metasomatically replaced at a very early stage in the consolidation of the granite through the action of volatile compounds. The origin of the garnet-sillimanite gneiss presents many puzzling features, but it is suggested that it originated in part from the combined effect of the destruction of amphibolite layers and of the concentration and precipitation of relatively volatile compounds of ferrous iron, alumina, soda, magnesia, and titanium locally in the border portion of the main magma body; and in part from pegmatitic solutions injecting, reacting with, and replacing amphibolite layers.

FEATURES OF THE WABASH SLUICEWAY OF NORTHERN INDIANA

BY CLYDE A. MALOTT AND ROBERT R. SHROCK

(*Abstract*)

The troughlike valley of the Wabash River in northern Indiana possesses some rather unusual features the significance of which has only been understood recently. Specially prepared topographic maps show the features in their true topographic relations. The characteristics of the valley-trough are such as to indicate that its form and features are the result of erosion by the glacial waters which escaped from the retreating Huron-Erie lobe and those which discharged westward from glacial Lake Maumee. It is cut 50 to 125 feet below the youthful glacial plain and is a veritable natural sluiceway inherited from the closing phases of the glacial period in northern Indiana. It is here designated a *sluiceway* because it is a troughlike runway through which coursed confined glacial waters of great volume.

The Wabash sluiceway would have been relatively simple had it everywhere been cut its full depth in glacial drift, but in many stretches the drift only thinly covers a buried limestone upland. In these limestone stretches the outer valley walls, composed of drift, are not always conspicuous or abrupt.

The sluiceway floor here has marked relief and possesses unusual features. These may be grouped under the terms *valley braids*, *scablands*, and *klintar*.

Valley braid is a term proposed for an individual runway of a valley which is in anastomosis, its valley parts passing about features in bas-relief or about upland tracts. The floors of the valley braids may be near the level of the one which carries the present stream or they may be much higher. Valley braids are numerous in some stretches of the Wabash sluiceway. Between Logansport and Georgetown, a stretch of six miles, no less than twenty valley braids are present. In one selected cross-section as many as seven occur. The present river channel chooses its way among them, as it were, and occasionally passes through one with vertical walls strikingly close together. A number of the valley braids have craggy sides of white limestone which rise wall-like above a flat muck-covered floor within reach of high flood waters. They range in width from narrow rocky floors a few yards across to mighty valleys a mile wide. The wide valley braids are in glacial drift. Perhaps a hundred or more valley braids occur between Huntington and Delphi.

Scabland surfaces of limited area are numerous in the limestone sections of the sluiceway floor. These are water-swept rock surfaces studded with rough masses, which rise above shallow fluves, and are frequently littered with a thin veneer of soil. They are present both on the upland patches between the rock-bound valley braids and on some stretches of the sluiceway floor not distinctly of valley braid character. The rock projections or "scabs" are weathered to a hackly roughness and some of them are so weathered as to resemble rock piles. They rise from a few feet to as much as twenty feet above the slightly veneered floors of the general scabland. The areas immediately west and east of Logansport constitute several square miles of scabland. In their characteristics they follow in miniature the scablands which Bretz has so ably described in the Columbia Plateau region of Washington.

The *klintar*, recently described in some detail by Mr. Shrock, characterize the limestone floor of the sluiceway between Huntington and Wabash. Numerous rather broad valley braids only a little above floodplain level pass about the upstanding, water-swept klintar whose craggy or blunt upstream ends are striking features indeed.

Every feature of the sluiceway aligns with the westward sweep of the great volumes of water which appear to have once raced over the broad floor or to have coursed through the valley braids at times to overflowing depths. Every feature, either positive or negative, owes its form to the erosive work of these waters that swept through the sluiceway valley, which itself was carved out of the youthland of a glacial plain.

Read by title.

ADDRESS OF THE RETIRING VICE-PRESIDENT OF SECTION E OF THE AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

By special arrangement, this hour was set aside for a joint session with Section E and the address of Prof. Charles Schuchert, retiring Vice-

President of Section E, entitled "Geological history of the Antillean region." Because of Professor Schuchert's illness, this address was read by Prof. C. O. Dunbar.

SYMPOSIUM ON CONTINENTAL PROBLEMS

A special symposium had been arranged by President Willis on subjects connected with the general field of the symposium and was presented at this time. To this series was given the rest of the morning session, under the chairmanship of President Willis.

METAMORPHIC OROGENY

BY BAILEY WILLIS

(*Abstract*)

Epeirogeny and orogeny constitute the theme. Geology gravitates gravely to gravity. Theories of orogeny, the contraction theory, the isostatic theory, know no force but gravity. The drift theory knows no force at all; and yet the earth is charged with energy.

Terrestrial energy appears as gravity, molecular forces, and heat. Gravity stabilizes. Molecular forces are potential. Heat is fluid. Terrestrial energy is manifested at the surface of the globe by balances that tend to maintain the *status quo*. Powerful disturbing forces are required to initiate change. Changes are introduced gradually, proceed spasmodically and locally, and cease. The processes call for the gathering of energy, the release of potential forces, the stabilization of the new state, and also for a mechanism through which the forces can work to produce the effects observed. The analysis suggests the concentration of heat, the release of molecular forces, and the alteration of rock masses in special situations, under special conditions.

The facts are: Continents are compressed. Compression has been irregularly periodic, exerted sometimes against one side, sometimes against another, but not simultaneously against opposite sides of any continent, but facing sides of two continents across an ocean basin have been thrust back from the basin contemporaneously. This means expansion of the ocean bed or of sections of it.

Concentrations of heat are characteristically, though now not exclusively, related with the basins of oceanic areas and mediterranea, as is shown by the distribution of volcanoes, etcetera. It is postulated, as set forth in continental genesis, that local rise of temperature by heating from within produces blisters (asthenoliths) in the asthenosphere at depths beyond 30 miles below the surface. Magma develops and flows out laterally, allowing the crust to sink, and a depression results. This process leads to the development of basins and continents by a long process of evolution.

Subsidence of the crust above a collapsing asthenolith results not only in a concavity on top, but also in convexity and tension below, thus affording opportunity for the intrusion of vertical dikes beneath the basin. Outflows of magma may result, but they are of less interest in connection with orogeny than are the dikes.

The crust of an asthenolith is relatively cool as contrasted with the magma and dikes rising into it will be chilled. The crust is vertically compressed by load in proportion to its depth, and this vertical pressure exceeds lateral resistance, especially after the margins have failed and lateral outflows have begun. The chilled dikes thus solidify under unbalanced stresses, and either in crystallizing from the magma or during later metamorphism, or both, will develop horizontal schistosity. The thrust of the molecules in adapting themselves to the stress environment is directed outward. The crust under the basin must expand and push away adjacent sections not similarly conditioned.

Continents are regarded as masses of predominantly acid rocks riding high as compared with the basins. The lateral pressure of the expanding basins is exerted against them 30 miles or more below their surfaces. They are underthrust by it and superficially appear to be overthrust toward the basins. Compression of the continental roots results in vertical extension and elevation of the surface. The horizontal pressure causes flat shearing planes to develop. They shear off a section of the margin of the continent and it is thrust upon the body. Friction is reduced by the intrusion of magma or by magma produced on the shearing plane. Folding and overthrusting of the sheared off spall results.

Where a strait, a geosyncline, lies between a continental mass and another continental, positive element, the latter may be sheared off, thrust forward, made a component part of the major continent. Sediments accumulated in the geosyncline will then be folded and overthrust.

Epeirogeny and orogeny are thus attributable to the expansion of the covers of asthenoliths in consequence of the combined action of gravity and molecular forces, energized by heat.

Brief remarks were made by Dr. W. Bowie, with reply by the author.

GEOLOGIC FACTS VERSUS THE ISOSTATIC THEORY

BY ROLLIN T. CHAMBERLIN

Read by title in the absence of the author.

CHARACTER AND HISTORY OF THE "CONTINENTAL NUCLEI"

BY CHESTER R. LONGWELL

(*Abstract*)

In each of the continents there is an ancient mass to which Dana's term *nucleus* may be applied. None of the masses is central, but several are framed on two or three sides by post-Cambrian sedimentary formations and zones of folding. The "nuclei" exhibit a general similarity in composition, in structure, and in the history of their vertical movements since early Paleozoic time. The points of resemblance and of difference will be discussed and Dana's ideas of "nuclei" will be examined.

Read by title in the absence of the author.

DEPARTMENT OF THE INTERIOR
U. S. GEOLOGICAL SURVEY

MAINE
(HANCOCK COUNTY)
LAFAYETTE NATIONAL PARK

68°28' 25' 20' 15' 10' 68°09' 44°30'

EXPLANATION

Park Limits

RELIEF

1262
Figures
(showing height above mean sea level instrumentally determined)

Contours
(showing height above sea, horizontal form, and steepness of slope of the surface)

DRAINAGE

Streams

Lake or pond

Marsh

CULTURE

Village

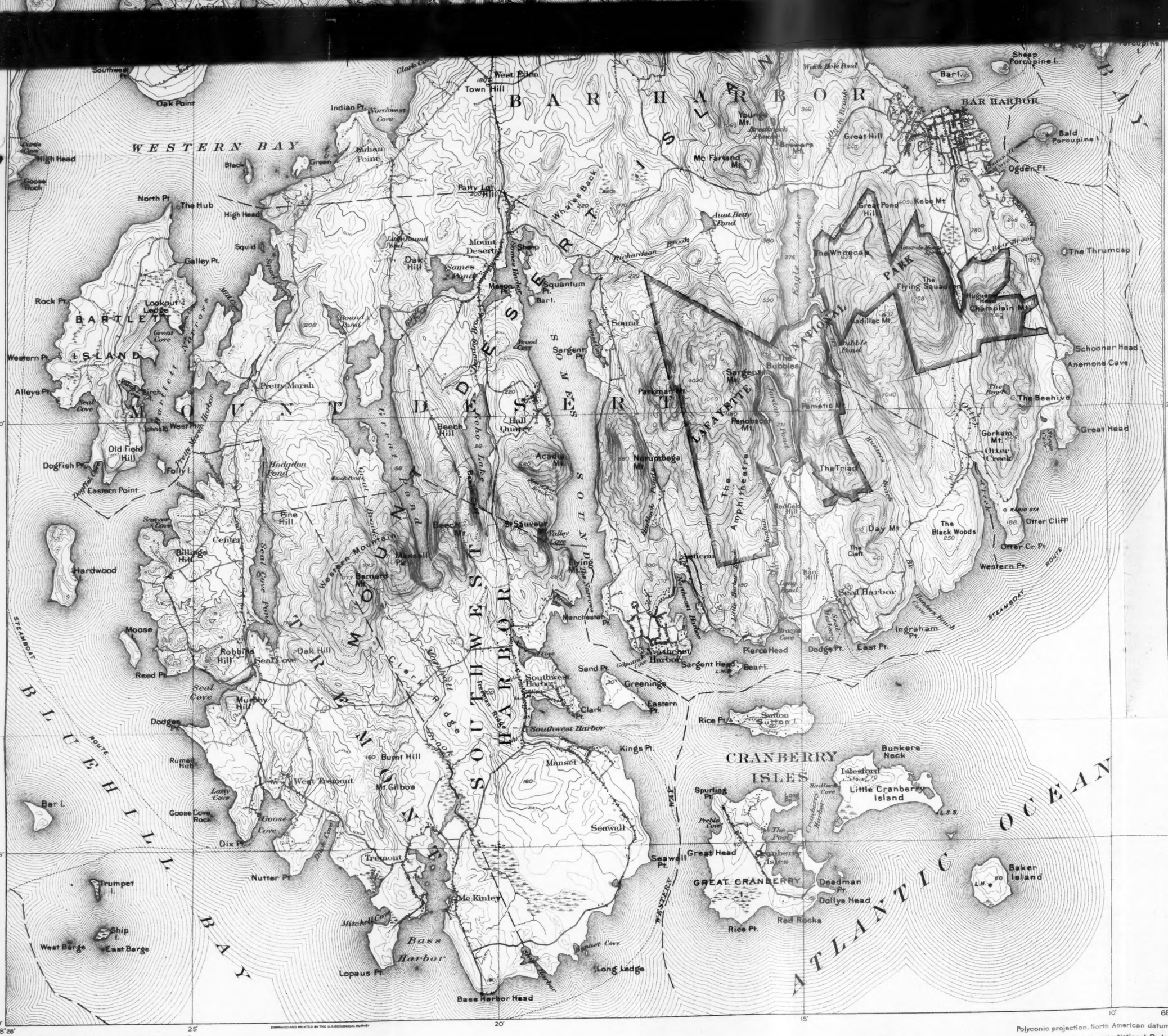
Roads and buildings

Church or schoolhouse

Secondary road

Railroad

Bridge



From U. S. Geological Survey topographic maps of Mt. Desert, Bar Harbor, and Swan Island quadrangles
Surveyed in 1901 and 1902

ENGRAVED AND PRINTED BY THE U.S. GEOLOGICAL SURVEY

Scale 1/62500
1 mile
1 kilometer

Contour interval 20 feet.
Datum is mean sea level.

APPROXIMATE MEAN DECLINATION 1922

Polyconic projection. North American datum

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LAFAYETTE NATIONAL PARK, ME.

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THE GEOLOGY OF MOUNT DESERT.

By George McLane Wood.[1]

A UNIQUE ISLAND ON OUR ATLANTIC COAST.

Mount Desert is the highest of the many islands that lie along the Atlantic coast of the United States, and it is the largest one that is composed of old crystalline rock. Long Island, N. Y., a good example of a lower coastal island, is much larger than Mount Desert, but it is made up chiefly of relatively soft glacial deposits and ocean-built sand bars, and so are the smaller islands of Marthas Vineyard and Nantucket. Long Island presents to the surge of the Atlantic a pliant beach that gathers to itself a great contribution of sea-borne sand, which, though locally shifted about by tides and currents, has been built up into a strand that stretches westward in an almost straight course for nearly a hundred miles; whereas Mount Desert opposes to the turbulent sea along a slowly wasting shore stubborn faces of hard rock, which, yielding unreadily to the attack of the waves, breaks down in huge masses whose continued opposition to the fury of the sea is made manifest here and there by high-thrown sheaves of spray and wildly swirling eddies. In this fierce contest the sea in storms has at certain places hurled such masses of rock, some of them weighing tons, above the level of the highest tide, forming a sea wall that reaches a height of many feet.

Long Island nowhere rises much more than 400 feet above the level of the sea and has an average altitude of less than 100 feet, whereas the top of Cadillac Mountain, on Mount Desert, stands 1,532 feet above the sea, and the island has an average altitude, according to Professor Shaler, whose estimate may be too high, of nearly 500 feet. Cadillac Mountain, formerly called Green Mountain, is not only the highest point on Mount Desert—it is higher than any other point within 20 miles of the Atlantic coast of the United States. Isle au Haut, about 15 miles to the southwest, has a maximum height greater than the average height of Mount Desert, but no other island on the coast is so high.

Mount Desert is remarkable for its large area as compared with the area of the neighboring islands and for its wealth of picturesque scenery. Most of the rocky isles off the coast of New England are less than ten square miles in area, but Mount Desert contains about a hundred square miles, and within that hundred miles it embraces scenic features that have long made it a place of popular resort and have led to the creation upon it of a national reservation that includes more than 5,000 acres of its most beautiful part—the Lafayette National Park, our only national park east of the Mississippi. The name given to this park recalls the fact that the island was first explored by another illustrious Frenchman, Samuel de Champlain, who, landing more than three centuries ago in the inlet now called Bar Harbor, named the island Mont-Désert.

The rocky isles of the Maine coast are peculiar, and their peculiarities are due to the geologic structure and history of the region in which they lie. They are the remains of old mountains, and their sizes and shapes are due to the sizes and shapes of the ridges from which they were carved by streams, glaciers, sea waves, and the agents of weathering, such as rain, frost, and geochemical action, and to differences in the resistance of the rocks of which the ridges were composed. Here the great natural destroyers have been at work, but with all their destruction—indeed, mainly as a consequence of it—they have created much of that picturesque beauty which gives to the coast of New England its commanding charm.

The central range of Mount Desert, according to Professor Shaler, who studied the island a generation ago, is in many ways the most interesting feature of its kind on our Atlantic coast. Its summits stand in a single line trending about N. 65° E. There are other similar ranges along the coast of New England, but none of them show so striking a linear arrangement. The alinement of the range and the uniformity of its structure indicate that the whole of it was originally united, though its individual summits are now separated from one another by deep, narrow valleys, some of which descend in places far below sea level.

Though the principal axis of the island thus trends about east-northeast, the valleys that intersect it, the deeper of them holding bodies of water, trend nearly north and south. How valleys so deep and of so strikingly uniform trend were cut straight across a hard mountain ridge is a problem for the geologist, but before this problem is considered it may be said that, by reason of the superior hardness of the granite of which it is composed, the range which dominates Mount Desert is a stubborn survivor of an ancient surface and that the beauty of the island as viewed from the sea, unparalleled along our whole Atlantic coast, is due to its retention of much of the height that it once shared with the surrounding region, which has been more rapidly worn away.

feldspar, white, gray, or pink, softer than the quartz and having smooth cleavage surfaces; hornblende, a greenish-black mineral whose particles are smaller than those of the other constituents; and in some places a brownish-black mica, which may be cleaved into minute thin plates.

The granite is cut by joints or breaks, along which it divides into blocks that are quarried for use as building stone. The United States Mint at Philadelphia, the basement of the New York Custom House, and the abutments and piers of the Highway Bridge over the Potomac at Washington are built of granite taken from quarries on the west side of Somes Sound in the neighborhood of the village of Hall Quarry. The manner in which the rock is naturally broken by the joints can be seen at many places, especially on the shore. It is along these joints that the blocks which make a sea wall have been broken off and afterward carried by storms above the level of high tide to form striking examples of natural masonry.

THE SEDIMENTARY ROCKS.

The great mass of igneous rock—a mass 12 miles long and 7 miles wide—which thus forms most of the surface of Mount Desert, though it underlies all the other formations, is not the oldest rock on the island; it is younger than the sedimentary beds against which it was thrust from beneath and into which it was intruded.

The sedimentary rocks of Mount Desert—those that were originally sediments deposited in water—were divided by Professor Shaler into several series. These sea-laid deposits derived from a rain-swept land would have formed a thick group, but erosion alternated with deposition, and the beds that make up the group are therefore nowhere found together in continuous chronologic sequence.

The oldest series of beds in this group of rocks originally consisted of deposits of mud and sand, which were in time consolidated to beds of shale and sandstone. The shaly beds were afterward changed by pressure, heat, and other agencies to a wrinkled greenish schist, a rock showing in some beds considerable folding and corrugation, and the sandy beds were changed to veinlike lenses of quartz or quartzite. This characteristic series, thin bedded yet having in the aggregate a thickness of not less than 2,000 feet, occupies part of the surface of the northwestern shore of the island and especially the west side of the adjacent Bartlett Island, whose name was applied to the series by Professor Shaler. The "Bartlett Island series," which lies low in the system of Paleozoic rocks—the oldest rocks that contain clearly identifiable remains of life—or perhaps even in the pre-Paleozoic (Algonkian) system, includes the oldest beds of rock on Mount Desert—beds that were originally formed when the site of the island lay at the bottom of a sea that was receiving the wash from an adjacent coast, in Cambrian or pre-Cambrian time, uncounted ages ago. The base of this series is not visible.

Upon the "Bartlett Island series," probably, were laid down in succession deposits that now consist of contorted schist and slate and sandy shale, found in scattered remnants along the eastern shore of the island from Cromwell Cove to Schooner Head and at places still further south and called by Professor Shaler the "Schooner Head series."

Still another series of sedimentary beds occupies the surface of the extreme northern part and the northeastern part of the island and is well displayed at Bar Harbor, from which it was named by Professor Shaler. The "Bar Harbor series" consists of thick-bedded flaggy slate, bluish-green and purple shale, and other sedimentary rocks, and its beds reach a maximum thickness of 1,000 feet.

None of these rocks contain fossils of any kind by which their age may be determined, but they were manifestly all originally deposits laid down on the bottom of an ancient sea, perhaps when the forms of life which then inhabited the earth had no hard parts that would be long preserved.

Minute study may discover interesting details of this chapter of the history of the island, but the visible record is fragmentary by reason of the erosion that has swept away much of the island and the submergence that has sunk a large part of it beneath the sea; and the remnant that still stands above the sea is blurred over by a sheet of glacial drift. Yet, as Professor Davis remarks, it is by putting together and comparing imperfect records like this, left at different places, that much of the geologic history of the world has been made out.

DIKES AND VOLCANIC ROCKS.

Dikes cut all the other rocks of the island at many places, on lowland and highland, from water's edge to mountain top. time to time, flows of lava and showers of ashes from volcanic vents somewhere in the neighborhood, although not a trace of such vents now remains.

SUMMARY OF THE PREGLACIAL HISTORY OF THE ISLAND.

The geologist has learned to regard the face of the land as a surface of shifting level with respect to the sea, for he can easily read in the geologic record unmistakable proofs of the uplift and depression of islands and continents. To him even "the eternal hills" are not at all eternal; they may be worn away in the course of geologic time, or they may be completely sunk beneath the sea. They are to him but fleeting forms on the ever-changing face of Nature. He recognizes the truth expressed in the familiar lines of Tennyson:

> There rolls the deep where grew the tree:
> O Earth, what changes thou hast seen!
> There where the long street roars hath been
> The stillness of the central sea.
>
> The hills are shadows, and they flow
> From form to form, and nothing stands;
> They melt like mists—the solid lands—
> Like clouds they shape themselves and go.

Uplift and subsidence mark the history of many lands, and the coast of New England is no exception to the general rule. It is now what is called a "drowned" coast—that is, it was submerged beneath the sea, probably by tilting, during the glacial period, in which the northern part of North America was covered with thick ice, though it has since been somewhat reelevated. The depression and reelevation, however, form but a single chapter in a long story of uplift, erosion, and subsidence that began countless cycles ago, in or before early Paleozoic time, when the earth was inhabited only by the lower forms of life.

If we could read this long and complex story of the geologic vicissitudes of the New England region fully and clearly it would doubtless seem to us animated and interesting, but the part of the record that now remains is only a fragment. Yet it is evident that in early geologic time sedimentation was going on in the area now occupied by Mount Desert Island. Sand and mud were being swept from inland down to the coast, and beds that formed sandstone and shale were being laid down in the quiet depths of the sea. This sedimentation did not take place without interruption. Uplift of the land at times brought the sediments above the sea, exposing them to erosion and partial removal, and later they were again submerged and other sediments were laid down upon their remnants. Subsequent uplift was accompanied by volcanic outbursts—by the pouring out of great lava flows and the ejection of fine igneous material.

Renewed subsidence was followed by uplift; the beds of sandstone and shale were raised up and folded and were invaded by the granitic magma, which, buried beneath a great thickness of sedimentary rock, cooled in a domelike mass. The compression thus produced further folded the beds, and by contact with the hot granitic magma the sandstone and shale were converted to quartzite, slate, and schist.

This uplift was followed by a long period of stability, during which not only much of the rock that covered the granite was removed by erosion, leaving mainly the present marginal remnants, but the granite itself was deeply eroded.

THE GLACIAL INVASION.

During the glacial period the climate of North America changed; epochs of arctic cold set in, and the northern part of the country was buried several times under vast sheets of slowly moving ice, every one of them such a sheet as now covers most of Greenland. Each of these great glaciers plucked many loose blocks from hard ledges and incorporated them into its mass and gathered up immense quantities of finer fragments of rock. Thus laden with a burden of clay and sand and gravel and great masses of rock it ground away the surface on which it rode and scored it with scratches (striæ) and with grooves; it widened and deepened valleys; and here and there, while it was melting, it laid down its burden in sheets, hills, and ridges of many sizes and shapes. Such material is called drift.

The ice overtopped the highest points on Mount Desert, and it must therefore have been not much less than 2,000 feet thick. The effects of the glacial invasion are graphically sketched by Professor Davis. Wherever the rocky floor of Mount Desert is freshly uncovered it is found to be more or less smoothed or rounded, as well as striated or grooved, by the gritty content of the great glacier, whose enormous weight, supplemented by a grinding tool so effective, made it a mighty agent of abrasion. Abraded surfaces may be seen at many points along the rocky shore of Mount Desert where the drift has lately been stripped off and the waves have not yet made successful attack. On

The loose drift by which much of the lower rocky floor of the island is covered shows at some places a structure that gives still further indication of glacial action. Its lower part, which lies closely packed on the striated bedrock, is a compact unstratified mass of stones, sand, and clay. Material of this kind, which is called till, was laid down by the glaciers during stages when they were melting and retreating northward. It is very generally spread over New England, where it diminishes the ruggedness of the rocky surface. Till also lies in the valleys, but there it is at many places covered with later water-washed sand or clay. The boulder-strewn ridge at the south end of Jordan Pond is probably a dump of drift—a moraine—formed at the end of one of the tongues of ice that occupied the gorges at the final stages of the last glaciation. The cemetery north of Seal Harbor stands on gravel that was washed from the moraine into the sea at the same time. Some morainal deposits are seen on Mount Desert, but the greater part of the material that was carried to the end of the glacier and that would have formed its terminal moraine must now lie south of the island, at the bottom of the sea.

Although the ice plucked many blocks from their native ledges, scraped off the preglacial soil and wore down the rock beneath, deepened valleys, and rounded off hills, yet a comparison of regions inside and outside of the glaciated area indicates that no considerable amount of erosion of the hard rocks can be attributed solely to glacial action. The excavation of the valleys by the long-continued action of streams was a large piece of work compared with the scraping of the surface by the ice sheet, yet on Mount Desert there are certain remarkable topographic features that must have been produced in great part by excavation by rough-shod ice. These are the deep valleys by which the mountain range is so peculiarly divided. In its length of 12 miles this range is notched almost down to sea level or even beneath it at no less than nine places. Instead of a mountain ridge as continuous as the granite surface farther north on the island, there is a diversified succession of rounded domes separated by deep gorges, and in nearly every gorge, almost directly in the axis of the range, there is a lake or an arm of the sea. This exceptional form is the result of glacial action on a mountain range that had been notched by stream erosion with transverse passes of moderate depth. The location and parallelism of the present deep gorges appear to be due to the control of erosion by vertical joints and dikes in the granite, and their remarkable profiles are the products of the work of glacial ice. The ice, crowding through the passes, plucked out and removed great quantities of the joint-riven granite and so assisted in making the gorges as deep as the open lowland on either side, or even deeper. The steps or benches seen on some of the cliffs were produced by glacial plucking aided subsequently by frost.

There is a striking coincidence between the trend of the systems of joints and the trend of the steep cliffs and slopes. This coincidence suggests that the gorges extend along zones of weakness in the rock. Still other cracks are produced by freezing, by the alternate expansion of the rock under the heat of the sun and its contraction at night, and by chemical action. The consequent increase in the number of cracks facilitates the entrance of water into the rock, and the water on freezing exerts great riving force, breaking off loose blocks, which are in turn by the same process broken into smaller blocks. In this way the rock is gradually reduced to fragments that can be swept along by streams.

The effect of the presence of a dike may be seen in the valley between Beech Mountain and the ridge just east of it, called Canada Cliff or Echo Mountain but not named on the map. In the middle of this valley, which is traversed by the road running from Carter Nubble toward Norwood Cove, there is an easily weathered dike, whose rapid removal by erosion has made the neighboring much jointed and altered granite accessible to weathering. The dike is about 10 feet thick, and the valley is about 200 feet deep. This valley may illustrate the conditions that determined the erosion of some of the other valleys.

POSTGLACIAL HISTORY.

During the last stage of glaciation the island was once more in part submerged, but it afterward rose again by a series of uplifts, between which there were halts of varying duration; yet it has not entirely regained the area it lost by that submergence. Many of the preglacial valleys and valley lowlands still remain sounds and bays, and the coast line is farther inland than it was in preglacial time. It is by reason of this submergence that Mount Desert and the many other islands that fringe the coast of Maine are separated from the mainland. All these islands were once hills on a coastal lowland.

its most beautiful part—the Lafayette National Park, our only national park east of the Mississippi. The name given to this park recalls the fact that the island was first explored by another illustrious Frenchman, Samuel de Champlain, who, landing more than three centuries ago in the inlet now called Bar Harbor, named the island Mont-Désert.

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ORIGIN OF THE GRANITIC ROCK.

The granitic rock that now forms most of the surface of Mount Desert was, long ages ago, intruded from below into older rocks as a plastic molten mass—a "magma." If the long-vanished surface of that time could be restored it would stand far above the present surface, for granite is formed from molten rock that lies at great depths, where it slowly cools and crystallizes. This hot granitic mass invaded the overlying beds of rock, cutting through them and incorporating fragments of them into itself. The granitic rock thus formed, now exposed to sight by the removal, through erosion, of the thick mass of sedimentary beds by which it was then overlain, affords at some places striking evidence of its mode of intrusion. The inclusion in the granite of angular fragments of older rocks and the penetration of the sedimentary beds of the island by granitic dikes show that the granite was forced into its present position while molten and that it slowly congealed into a rigid mass that held within itself fragments gathered from the rocks it had invaded. "The bare ledges and cliffs of Hunters Beach Head [east of Hunters Beach Cove], as well as of many other similar points on the southern coast," writes Professor Davis, "afford wonderfully clear illustrations of the processes of the granitic intrusion. Here we may follow the granite wedging its way into narrowing cracks among the older rocks . . . The granite rock, now so rigid, then so liquid, or at least then yielding so perfectly under the pressures that were exerted on it, entered into the narrowest little crevices, following them down to hairlike fineness. Nowhere in the world may the traveler find better illustrations of the manifold processes of deep-seated intrusion than are here exhibited on the wave-swept ledges of the southern coast east of Somes Sound."

The minerals that form the granitic rock can be easily seen with the unaided eye. They are quartz, translucent and glassy;

[1] Compiled from papers by Nathaniel Southgate Shaler and William Morris Davis and from a manuscript furnished by Mr. George B. Dorr, superintendent of the Lafayette National Park. Professor Shaler's paper was published in the Eighth Annual Report of the United States Geological Survey, in 1889, under the title "The geology of the island of Mount Desert, Maine." Professor Davis's paper formed a part of a book on the flora of Mount Desert by E. L. Rand and J. H. Redfield, published in 1894, and was entitled "Outline of the geology of Mount Desert." Use has also been made of a paper by Professor F. Bascom on "The physiography of Mount Desert," published in the Bulletin of the Geographical Society of Philadelphia for October, 1919 (vol. 7, No. 4). The text has had the benefit of criticism by Mr. W. C. Alden, Mr. Laurence LaForge, and Mr. Edward Sampson, of the U. S. Geological Survey.

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DIKES AND VOLCANIC ROCKS.

Dikes cut all the other rocks of the island at many places, on lowland and highland, from water's edge to mountain top. These walls, so to speak, set into older rocks, were intruded into them in a molten state in cracks or along zones of fracture or weakness. The dikes are of different thickness, and they consist of rocks of different kinds. The oldest, which are no doubt older than the granite and which are found around the edges of the island, are formed of a rock that Professors Shaler and Davis call felsite—a compact rock whose main body or groundmass is made up of minerals so small that they can hardly be seen with the naked eye but which contains in its fine-grained groundmass well-defined crystals of feldspar and quartz and is therefore said to be porphyritic, because its texture is like that of the porphyry of ancient fame and favor.

Masses of old dark crystalline rock called diorite and gabbro are found along the western coast of the island, and still other masses, which were formed later and are much thinner, composed of a dense, hard dark-green fine-grained rock known as trap, are widely distributed over the island. A straight line a thousand feet long drawn almost anywhere on the island from east to west will cross one or more dikes. Granitic dikes were thrust out from the central mass of granite. A granite mass forms Baker Island, and similar masses may be seen on the south shore of Mount Desert at Seawall Point and farther southwest. Another similar dike is seen on the shore of the island at Dix Point.

On the northern shore of the island, in its southwestern part, and on several of the smaller islands to the southeast there are some bodies of old volcanic rock—a felsitic lava. It is of crystalline texture, but it is much finer grained than the granite of the central belt, and in places it is arranged in sheets or flows that lie parallel with the beds of the adjacent sedimentary rocks. At some places it has a porphyritic fabric; at others it has a banded appearance due to flow while it was molten; and at many places it is broken or brecciated as if by movement that continued after a part of its mass had become solid. A volcanic breccia is seen in the rock on the eastern shore of Bass Harbor. Associated with the denser lavas are large fragmental and ashlike deposits, which appear to have been formed by explosive eruptions from some neighboring volcanic vent whose location is not known. Dikes of felsitic rock at some places cut through the bedded rocks and are in turn cut by the granites, as may be seen along the shore east of Bass Harbor. All these features suggest that the felsitic lava marks a period of volcanic activity that formed a part of the time during which the sedimentary series were being laid down in the sea. The sandy or muddy bottom of that sea must have received, from

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the quiet depths of the sea. This sedimentation did not take place without interruption. Uplift of the land at times brought the sediments above the sea, exposing them to erosion and partial removal, and later they were again submerged and other sediments were laid down upon their remnants. Subsequent uplift was accompanied by volcanic outbursts—by the pouring out of great lava flows and the ejection of fine igneous material.

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A notable transportation of boulders was associated with the glacial scoring and followed the same direction. Boulders of the easily recognized greenish schist of the western coast of the island have been carried far from their parent ledges to areas underlain by rocks of other kinds. Boulders of the granite of the central granitic mass have been carried southward over the surface of the bedded and volcanic rocks. The glacial transportation of masses of rocks was not confined to the island, which, let us remember, was once part of the mainland, for blocks of a coarse gray granite, easily known by its large crystals of whitish feldspar but not seen in its original place on the island, are found here and there on the surface. These "erratics," as they are called by geologists, were brought by the ice from what is now the mainland, where granite of this kind is common. One of these boulders was to be seen, some years ago, near the summit of Cadillac Mountain. Balanced Rock, on the south peak of The Bubbles, is one of many such erraties, and a large erratic stands on the summit of Penobscot Mountain.

Transported fragments of a fossiliferous shaly flagstone, most of them less than a foot in diameter, are sparingly distributed over the western half of the island. These fragments are easily identified as having been derived from beds of Devonian rock that lie many miles north of the coast of the mainland. Such rock in its original place has not been found anywhere on the island.

Nearly all of this transportation of boulders is the work of the ice sheet, which, however, was at some places aided by subglacial streams—streams that flowed beneath the ice near its southern margin. The boulders are simply the larger fragments that the glacier dragged along beneath it or carried in its lower part. A few of these boulders may have been carried on icebergs broken from the ends of glaciers at the ice front in the sea and dropped to the bottom—now dry land—when the icebergs melted or shifted their positions in the water through changes of form due to breakage and readjustment of balance.

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The effect of the presence of a dike may be seen in the valley between Beech Mountain and the ridge just east of it, called Canada Cliff or Echo Mountain but not named on the map. In the middle of this valley, which is traversed by the road running from Carter Nubble toward Norwood Cove, there is an easily weathered dike, whose rapid removal by erosion has made the neighboring much jointed and altered granite accessible to weathering. The dike is about 10 feet thick, and the valley is about 200 feet deep. This valley may illustrate the conditions that determined the erosion of some of the other valleys.

POSTGLACIAL HISTORY.

During the last stage of glaciation the island was once more in part submerged, but it afterward rose again by a series of uplifts, between which there were halts of varying duration; yet it has not entirely regained the area it lost by that submergence. Many of the preglacial valleys and valley lowlands still remain sounds and bays, and the coast line is farther inland than it was in preglacial time. It is by reason of this submergence that Mount Desert and the many other islands that fringe the coast of Maine are separated from the mainland. All these islands were once hills on a coastal lowland.

Among the evidences of postglacial subsidence followed by uplift are deposits of marine clay that were laid down upon the glacial drift. A deposit of such clay east of Seal Harbor, containing marine shells, lies about 100 feet above the present sea level. Sea caves may be seen at some places high up on the slopes. On the east face of Gorham Mountain, at a point more than 200 feet above the sea, there is an ancient sea cave, and traces of beach and delta deposits have been noted elsewhere at about the same level. Some of the deposits of stratified sand and gravel seen at several places, as at the Bar Harbor golf links, were probably laid down at the time these beaches and deltas were being formed.

Since the land reached its present height the sea has begun to make its marks along the shore. Where the shore line is a steep cliff of hard rock and the waves cut into its base faster than the slope above is washed away they have formed caverns, but only at places where they have been aided by joints or other lines of structural weakness in the rocks. Generally the face of the slope is wasted away as fast as the waves undercut its base, and thus is formed, a little below water level, a rocky bench that is surmounted by vertical faces like those at Great Head and Otter Cliff. The waves have not only attacked and broken down rocky faces along the shore but have at a few places built up bars and beaches. At the head of Bracy Cove, west of Seal Harbor, they have built a striking barrier beach that cuts off an inlet from the sea, forming Long Pond. They have also formed the bar that connects Bar Island with Mount Desert and that has furnished the names of that island and of Bar Harbor.

Professor Davis concludes his outline of the geology of Mount Desert with reflections that seem befitting a thoughtful summer sojourner on this enchanting isle on a leisure day and that may be transcribed here to complete this brief sketch—transcribed not quite literally, yet with full recognition of the fitness of their thought and spirit:

As the waves now rise and fall along the shore in broken rhythm, as the tide ebbs and flows across the strand, so the seas of other times have risen and fallen and ebbed and flowed in uneven measure on the uneasy land; the rocks have grown and wasted; the ice of the North has crept down and has melted away—all these and still other scenes have been shifted slowly back and forth in a great drama of unending change. What lies before us here to-day is only one scene of the many that have been unfolded through the immeasurable past.

May, 1924.

PALEONTOLOGICAL EVIDENCE BEARING ON THE PROBLEM OF THE PERMANENCE OF CONTINENTS AND OCEANS

BY PERCY E. RAYMOND

(*Abstract*)

Since no one questions the permanence of the Pacific Ocean, this discussion relates chiefly to the Arctic and Atlantic. The distribution of modern marine benthonic mollusca along the western coasts of Europe and Africa shows the existence of distinct faunal subregions, and the eastern coasts of North and South America have similar ones. The distribution of the fossils in the Cretaceous and Tertiary deposits on both sides of the Atlantic show that practically the same subregions are recognizable in the past, with about the same amount of difference in faunas on opposite sides of the ocean as at present. Lack of coastal deposits of greater age prevent further comparison on this line, although there is some evidence as far back as the Permian.

During the Paleozoic there was opportunity for intermigration of marine animals between North America and Europe by way of the Atlantic in Cambrian, Ordovician, Silurian, Lower Devonian, and Mississippian times. Communication by way of the Arctic was open in Upper Cambrian, Ordovician, Silurian, Middle and Upper Devonian, Mississippian, and Pennsylvanian times. Whether it was by way of open oceans or the troughs of geosynclines can not be proven by the fossils, but the facts bearing on the subject will be discussed. The length of time which it took certain sorts of animals to make the journey appears to indicate that the route was probably a circuitous one about the shores of an ocean, rather than a direct one along geosynclines. The distribution of fossils does not seem to indicate that the continents were ever closer together than at present. That Asia has had about the same position in relation to North America as at present is shown by the faunas of the Middle and Upper Cambrian, Ordovician, Mississippian, and Mesozoic.

SOURCE OF PLATEAU BASALTS

BY N. L. BOWEN

(*Abstract*)

Most hypotheses of the source of the great basaltic floods have sought it in a layer of the earth of basaltic composition. The present paper discusses the possibility that the magma originates in the selective fusion of a peridotite zone of the earth.

Brief remarks were made by Messrs. R. A. Daly and Bailey Willis, with reply by the author.

NATURE OF THE OROGENIC PROCESS

BY W. T. THOM, JR.

(*Abstract*)

It is believed that recent contributions, both as to fact and hypothesis, have brought us to the point where the nature of the orogenic process can

be visualized with some certainty. Salient beliefs forming parts of this synthesis are:

1. That the earth's crust is essentially in isostatic equilibrium.
2. That large-scale thrust-faults and great fold systems exist.
3. That rocks marking old climatic zones appear to have shifted widely from their original position.
4. That because of 1 and 2, and perhaps 3, the crust evidently is capable of horizontal shift with respect to the centrosphere, or, in other words, that a subcrustal zone of (mainly solid) flow must underlie the rigid crust.
5. That the periodicity of orogenesis indicates a continuously active cause of thrust, with periodic relief of accumulated elastic stresses.
6. That the opposition of stress relief, and of frictional resistance to rapid movements, causes the pulsations characteristic of orogenic revolutions.
7. That the periods of normal faulting which follow ones of thrust-faulting indicate that stored elastic stresses are completely relieved during an orogenic revolution.
8. That both radioactivity and frictional heating under isostatic readjustment (induced in turn by solar energy) cause subcrustal temperatures to rise during periods of crustal calm.
9. That the fusion and rise of magmas and the rise of gases and vapors give escape to this surplus heat during or just after the maximum phase of the revolutionary episode.
10. That gravity is the only force known to be adequate to cause observed lateral thrusts.
11. That shrinkage due to simple cooling of the globe is inadequate as a sole cause of orogeny.
12. That radial shrinkage due to molecular rearrangement may or may not be adequate as a cause of observed tangential thrusting.
13. That crustal extension (as well as nuclear contraction) must be an important cause of crustal deformation.

At the conclusion of the symposium opportunity was given for the presentation by Professor Mather of a reel of motion pictures.

MOTION PICTURES FOR CLASSROOM INSTRUCTION IN GEOLOGY

BY KIRTLEY F. MATHER

(*Abstract*)

For several years the writer has been experimenting with motion pictures as an aid in class-room instruction in both his elementary and advanced classes in geology. During the past year he has been systematically cooperating with Pathé Exchange, Inc., in the preparation and production of a series of films entitled "The Structure of the Earth," especially intended for use in class-rooms. Selected portions of these films, most of which have not yet been released for general use, will be presented.

Certain phases of class-room instruction can best be developed by oral discussion, others by formal lectures, others by a study of maps, diagrams and charts, others with lantern slide illustrations, and still others with motion pictures. The motion picture should be used solely for these latter phases of

instruction. Thus it becomes an additional tool which may be acceptably used by the teacher. For example, two or three moments spent in observing a motion picture of a river in flood, or of waves breaking on a storm-racked coast, or of the eruption of a volcano, give to the student a much better impression of the real nature of these phenomena than can be obtained in any other way. Laboratory experiments such as those made on a "stream table" may be presented for a large class without loss of time or without the danger that the desired phenomena may fail to appear to the best advantage. Animated drawings may be used to illustrate such obscure features as the transmission of earthquake vibrations through the interior of the earth and the method of recording them on seismographs.

These and other ways in which motion pictures may be adapted to geological instruction were discussed and illustrated.

At approximately 1:15 p. m. the session adjourned for luncheon.

SESSION OF FRIDAY AFTERNOON

The afternoon session was opened at 2:20 o'clock, in the Duplex Assembly Room, School Service Building, with President Willis in the chair.

TITLES AND ABSTRACTS OF PAPERS

FALCON ISLAND

BY J. EDWARD HOFFMEISTER, HARRY S. LADD, AND HAROLD L. ALLING

(Abstract)

Falcon Island, a South Pacific volcano in the Tongan group, twice destroyed by wave action in the past, was built above sealevel for the third time in October, 1927. It was observed in violent eruption in the early part of May, 1928, and was visited two weeks later, at which time it was steaming quietly.

The island is two miles in diameter and rises to an elevation of 365 feet. It is composed entirely of pyroclastic material, chiefly ash and scoria. The crater lies to windward and is occupied by a boiling lake whose waters rise and fall with the tide. Steam and sulphurous gases arise from the lake and from numerous fumaroles surrounding it. Sulphurous deposits veneer the crater walls.

Already the trade winds have cut steep cliffs to windward and have built an extensive shoal to leeward. If no further volcanic action occurs, the island will be destroyed by the waves within a few years.

Petrographic studies have been made of the material collected.

ORIGIN OF CONTINENTAL ABYSSAL SLOPES

BY F. P. SHEPARD

(Abstract)

The presence of a relatively steep slope terminating the continental shelves has been known for more than a century, but no serious attempt has been made to explain this phenomenon. Coastal surveys and oceanographic ex-

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The presence of a relatively steep slope terminating the continental shelves has been known for more than a century, but no serious attempt has been made to explain this phenomenon. Coastal surveys and oceanographic ex-

peditions have accumulated a considerable quantity of information concerning these slopes. An analysis of almost all of these data was made as a basis of the present work. Hundreds of profiles have been constructed; the character of the outer edge of the shelves has been examined along with that of the slopes beyond; the types of sediment for these areas have been noted and compiled from the charts, and other methods have been employed to obtain all possible light on the problem of the origin of the slopes.

It is concluded that the greater part of the abyssal slopes are fault-scarps, reduced from their original steepness by sediment washed over the edge of the shelves and by submarine landslides. Among the evidences which were thought to support this hypothesis are the existence of numerous slopes off all types of coasts with a steepness comparable to land fault-scarps, the typical landslide profiles of the slopes, and the association of earthquake epicenters with many of them. That the sediments from the lands have not extended the continental shelves as wave-built terraces or deltas is suggested by the presence of many hills along the outer edges of the shelves and by the exposure of rock bottom in many places both on the edge and abyssal slopes. The alternative that the sediments from the lands have slumped and slid down the fault-scarps is suggested.

GEOLOGY OF MOUNT DESERT ISLAND, MAINE[1]

BY CHARLES WILSON BROWN

(*Abstract*)

This topographically prominent area, which includes the Lafayette National Park on our Atlantic coast, presents many interesting problems in igneous, metamorphic, and physiographic geology. The ancient Ellsworth schists and the later Bar Harbor sediments, 700 to 800 feet (the lower Cambrian age will be discussed in a later paper) and related agglomerates have been severely brecciated and much altered by a series of plutonic rift injections. Revising previously published reports, first in order came a dioritegabbro, then a hornblende granite which forms the bulk of the island, and a commercial biotite granite not hitherto outlined. Probably associated with the first and last of the abyssal intrusions, came, respectively, basic sills and flows now much changed and acid rhyolite-dacite dikes, sills, and flows. All formations have been extensively cut by two sets of trap dikes, probably of Triassic age. The bold relief of this region, produced by differential erosion in rocks of widely varying resistance, gives abundant opportunity to study the igneous and metamorphic history. The fiord coast shows many fine examples of shoreline features and in the high marine fossiliferous clays proofs of post-glacial uplift.

EXPERIMENTS IN SOIL FREEZING

BY STEPHEN TABER

(*Abstract*)

Pressure effects accompanying the freezing of soils are due to the growth of ice crystals and not change in volume. The pressure is developed only in

[1] By permission of the Director of the U. S. Geological Survey.

the direction of crystal growth if the pressure does not exceed the crushing strength of the ice or the material with which the ice crystals are in contact. The direction of crystal growth is determined chiefly by the direction of cooling.

Heaving in excess of that which could be explained by change in volume of the water present is common. It is due to the segregation of water as it freezes, additional water being drawn up by molecular cohesion. The chief factors controlling segregation and excessive heaving are: size of soil particle, amount of water available, size and percentage of voids, and rate of cooling.

Frost heaving when uniform causes little cracking of pavements or disturbance of structures; but differential heaving is very destructive. Local differences in soil texture and in the amount of available water are the major causes of differential heaving, but differences in the kind and amount of soil cover are also of importance.

As a result of freezing followed by thawing, more water may be concentrated directly under pavements than in any other way. This is conducive to unequal settling, especially on slopes, and the resulting damage to pavements is probably greater than that which may be attributed directly to frost heaving. A sudden drop in temperature after a thaw has left an excessive amount of water in the surface soil is a condition especially favorable for segregation and excessive heaving.

Segregation of water on freezing causes shrinkage cracks if the supply of water is limited or if the soil is very impermeable because of high colloid content. In the latter case the cracks are largely filled with ice. The shrinkage due to withdrawal of water to form ice results in a columnar structure which advances downward as freezing progresses. It furnishes a logical explanation for the soil polygons, with convex surfaces found in certain cold regions.

CASES OF FLOOD EROSION IN VERMONT

BY ELBRIDGE C. JACOBS

(Abstract)

Views were shown of some interesting cases of erosion produced by the flood of November, 1927.

At Hardwick, on the headwaters of the Missisquoi River, Mackville Pond, which is perched in the unconsolidated delta material of the region, broke through its bank and carved out a gully some 50 feet deep, 80 feet wide, and 400 to 500 feet long. This gully uncovered a transverse ledge of slate on which are glacial grooves and two sets of glacial striæ.

At Waterbury, on the Winooski River, the flood exposed the old stream bed, laying bare large potholes and stream channels, eroded in the ledges of schist which strike across the valley.

At Cavendish the overflowing Black River flooded the village and eroded a great gully along the highway leading to the Connecticut River. This gully revealed the preglacial bed of the stream, which now flows through a gorge on the opposite side of the valley.

At Gaysville the White River, previous to the flood, had been flowing in a small postglacial gorge on the south side of the valley. The rest of the valley was mantled with glacial till, while the town stood on either side, as well as across the valley, in the shape of letter H. The flood swept away the glacial fill and the structures on it, allowing the river to resume its preglacial channel on the north side of the valley.

Brief remarks were made by Messrs. Kirk Bryan and F. J. Pack.

METHOD OF COMPUTING MECHANICAL COMPOSITION TYPES IN SEDIMENTS

BY CHESTER K. WENTWORTH

(*Abstract*)

The mechanical composition of a sedimentary rock is one of its most distinctive characteristics. Fundamental data in the case of unconsolidated material are obtained by sifting or by elutriation. Representation of these data as a series of figures in tabular form is comparatively unsatisfactory and their portrayal in graphical form, though more vivid, lacks the flexibility of comparison so much needed in this field.

There are various well established computing methods used by statisticians in dealing with frequency distribution problems in economics, biometry, and other such subjects and the present study is an attempt to adapt the most essential of these methods to the investigation of size distribution in sediments. A routine computing procedure has been worked out which is adapted to the particular data resulting from mechanical analysis and requiring but a very few minutes for application to each sample of sediment. Within the limits of accuracy permitted by the original data, constants are derived which express the average coarseness of the material, the amount of deviation from perfect sorting, and the skewness or asymmetry of the distribution of particle sizes about the mean.

These index numbers expressing the shape of the distribution curve are thus available for averaging in groups to indicate the characteristics of composition of sediments of different types and for comparison with those of sediments of known origin in interpreting the genesis of ancient sediments. It is evident that as an increasing body of data in this field are available and are reduced to general numerical indices of this or a similar type, comparisons between sediments will be greatly facilitated and as a diagnostic feature mechanical composition can be put to far more practical and precise use than has been the case in the past.

Brief remarks were made by Prof. Alfred C. Lane.

INITIAL DIPS PERIPHERAL TO RESURRECTED HILLS

BY C. L. DAKE AND JOSIAH BRIDGE

(*Abstract*)

Steep dips at the contact of Cambro-Ordovician sediments against Precambrian porphyry knobs are described, and evidence advanced to show that

these dips are initial, rather than the result of tangential thrust, unequal compacting, or settling from solution.

FACETED PIEDMONT SPURS OF DESERT RANGES

BY CHARLES KEYES

(*Abstract*)

Next to rearing themselves above the illimitable plains-surface all about, as volcanic isles out of the sea, the Great Basin mountains, and desert ranges in general perhaps, present, as an outstanding feature, a conspicuous truncation, at their lower ends, of the transverse ribbings of the mountain-flanks, where the latter meet plain. This faceting of the piedmont spurs is often assumed by the physiographers to be a direct expression of major faulting marking out the orogenic blocks, and is thus invoked as indisputable evidences of the verity of the Gilbertian hypothesis of buoyant mountains.

It is unfortunate that the supposed examples are taken entirely from within the tract of the Quaternary Great Salt Lake, or Lake Bonneville; for here, of all places, there is the most uncertainty regarding the specific cause of piedmont faceting. The fault theory is only one of several possibilities. There are at least three others of which little is made. Gilbert himself shows that faceting may also be produced by wave-action, and gives diagrams and views of the old Bonneville shorelines to demonstrate it. There is the thrust-block scarp which is displayed in some of the Great Basin ranges. Then there is the eolic explanation in which the action of wind-scour is at maximum where mountain meets plain, with a resultant of a girdling of the ranges as by a sea-cliff. The fault hypothesis is as yet only very poorly supported from the thousand and one desert ranges which should present evidences aplenty. Nor are the other possibilities excluded. Wind-scour girdling seems to hold good for many desert ranges outside of the Great Basin and where faulting is convincingly precluded.

Read by title.

EVIDENCES OF ISOSTATIC ADJUSTMENT IN THE FRONT RANGE

BY DANIEL F. HIGGINS

(*Abstract*)

Work on the Rocky Mountain structure, by Lee, Chamberlin, and others, is briefly reviewed. Evidence is presented from many sources to show what the character of the vertical displacements in the Front Range has actually been in Tertiary time. In this evidence are presented results from the writer's detailed field-work over a large area in northern Colorado. It is concluded that the ample field evidence shows action of isostatic adjustment of the earth's crust in the region of the Front Range during Tertiary time.

Read by title.

JOINT SESSION WITH THE PALEONTOLOGICAL SOCIETY

At 4 o'clock, the hour announced for the joint session with the Paleontological Society, the meeting was taken in charge by Vice-President August F. Foerste and the following papers were presented:

TITLES AND ABSTRACTS OF PAPERS

TULLY FAUNA AT THE BASE OF THE BLACK SHALE IN EAST-CENTRAL KENTUCKY

BY T. E. SAVAGE

(*Abstract*)

East of the Cincinnati anticline, in Estill and Powell counties, Kentucky, the Upper Devonian strata are represented by a bed of hard, black, laminated shale which ranges in thickness up to 135 or more feet. In the lower 10 or 15 feet of this shale there are lenses and bands of rather fine sandy, magnesian limestone, from 2 or 3 inches to as much as 8 or 10 inches thick, interbedded with the black shale. At the base of the shale there is commonly a single layer of somewhat sandy, magnesian limestone, called by Foerste the Duffin layer, which ranges from 2 to 5 feet in thickness. This Duffin layer belongs to the age of the black shale deposition, as is shown by the fact that in several places a thickness of a few inches of black shale is present beneath it.

The Duffin layer, and some of the lenses of sandy, magnesian limestone ten or more feet above the base of the black shale, furnished such fossils as *Ambocoelia* cf. *umbonata*, *Camarotoechia* cf. *sappho*, *Chonetes* cf. *mucronatus*, *Hypothyris cuboides*, *Leiorhynchus quadricostatus*, *Martinia subumbona*, and *Spirifer pennatus* var. *tulliensis*.

Of these species, *Hypothyris cuboides* is thought to indicate an age corresponding to that of the Tully of New York, and the associated species are not inconsistent with such a correlation. This would indicate that the black shale deposition in this part of Kentucky began as early as Tully time.

Read by title in the absence of the author.

SILURIAN OF THE CENTRAL APPALACHIANS

BY CHARLES K. SWARTZ AND FRANK M. SWARTZ

(*Abstract*)

The authors have been engaged for a number of years in the study of the Silurian formations of the region between the Delaware River and northeastern Tennessee. Sections, many of them closely placed, will be shown exhibiting the character of the Silurian formations of this region and a correlation will be given based upon the sections and their faunal zones.

Some of the results believed to be established are the following: The Clinch sandstone of Safford, the upper division of the Massanutten sandstone of Virginia, the Tuscarora of Maryland and central Pennsylvania, and the Shawangunk of eastern Pennsylvania are continuous. The Clinton may be traced throughout the region, its Keefer sandstone member being widely per-

sistent. The Sneedsville limestone of Tennessee is continuous with the Tonoloway limestone of Maryland and central Pennsylvania and the latter, in part at least, with the Bossardville of eastern Pennsylvania and New Jersey.

The relations of the marine McKenzie, the Wills Creek, and the continental Bloomsburg are shown and the correlation of the latter with the Vernon and High Falls red shale of New York suggested.

CORRELATION OF THE CAMBRIAN SEDIMENTS AT NAHANT, MASSACHUSETTS, WITH THE BAR HARBOR SERIES

BY CHARLES WILSON BROWN

(*Abstract*)

Throughout northeastern New England there are widespread but sporadic occurrences of the fine-grained, even-bedded, purplish, quartzose flagstones, which point to a period at the beginning of the Paleozoic of abundant though quiet sedimentation throughout this area. The lithologic responses of these rocks to slight or great metamorphism under similar conditions but in different localities are peculiar, constant, and easily recognized. In spite of the separation of these sediments by the irregularities of the Maine coastline and by extensive batholithic intrusions, a careful study of the different occurrences of these flagstones at Nahant, probably Braintree, Biddeford, North Haven, Mount Desert on the coast, and about Bangor, Houlton, and North Anson Falls in the interior, warrants the presentation of these tentative conclusions that Schuchert's Acadian trough should be extended westerly.

COMANCHEAN REPTILES FROM KANSAS, OKLAHOMA, AND TEXAS

BY CHARLES N. GOULD

(*Abstract*)

In 1893, and again in 1895, the writer discovered bones of Plesiosaur in the Kiowa shales of Clark County, Kansas. These fossils were named by S. W. Williston. In 1909 Pierce Larkin discovered fragments of a bone of a dinosaur in the Trinity sandstone near Atoka, southern Oklahoma. During the past twenty years dinosaur tracks have been found in the Glenn Rose formation, of middle or upper Trinity age, in various counties in Texas. The last discoveries of tracks of this kind were made in Kinney County, Texas, during the past summer. These tracks, which are described herein, are 21 inches long and average 15 inches broad. The animal had a stride of 5 feet 3 inches.

Brief remarks were made by Messrs. G. R. Wieland and J. J. Galloway.

HILLSBORO SANDSTONE OF OHIO

BY J. ERNEST CARMAN AND ERNEST O. SCHILLHAHN

(*Abstract*)

The Hillsboro sandstone, exposed in Highland County, Ohio, was named by Orton who gave sections showing it either interbedded in the upper part of the Niagaran or resting on Niagaran. Prosser later published sections showing it interbedded in both Niagaran and the overlying Monroe (Greenfield).

The authors of this paper have shown that all the exposures previously interpreted as sandstone layers interbedded in the Greenfield and the Niagaran dolomites are really more or less irregular masses of sandstone completely enclosed in the dolomites not more than 30 feet below the Silurian-Devonian disconformity which in this region truncates the Greenfield and Niagaran dolomites. The other exposures are at the horizon of the disconformity resting on either the Greenfield or the Niagaran.

The Hillsboro sandstone therefore includes two types of deposits of the same age: (1) discontinuous sand deposits laid down on the post-Silurian erosion surface on either the Greenfield or the Niagaran; (2) sand that was washed down into and filled existing cavities and open joints beneath this erosion surface in either the Greenfield or the Niagaran. By this interpretation, it is younger than the erosion interval which came some time after the formation of the Greenfield dolomite of late Silurian and older than the Ohio shale of upper Devonian, which, in this region, lies next above the Silurian-Devonian disconformity. It is in the same hiatus as the Sylvania sandstone of early Devonian age of northwestern Ohio, but this hiatus in Highland County extends farther downward and farther upward.

NEW TRIASSIC FOSSIL LOCALITY

BY MALCOLM R. THORPE

(*Abstract*)

In October, 1926, a slab of red Triassic sandstone, bearing a natural cast of a dinosaur footprint, was discovered a few miles east of New Haven in an area which had hitherto produced no fossils of any kind. This footprint was figured and described by Professor Lull as *Anchisauripus tuberosus* (E. Hitchcock). The locality was at the site of the new dam of the New Haven Water Company, at North Branford, about 8½ miles slightly north of east of New Haven, Connecticut. Subsequent exploration at this site resulted in the discovery of two more tracks (*Anchisauripus* and *Eubrontes*) in the red and gray sandstone strata, while in the black shale several fossil fishes (*Semionotus* and *Catopterus*) were collected, together with fragments of fossil wood.

In connection with this new reservoir an inlet tunnel was bored a continuous distance of 13,503 feet, in a nearly east-west direction, under Sea Hill and the Sugar Loafs, the tunnel being known as the Sugar Loaf Tunnel. The West Portal of this tunnel is approximately 2 miles north of the dam. The tunnel penetrates the Triassic posterior shales and sandstones throughout its entire length, cutting across about 350 feet of the formation.

Fifty-six footprints were recovered from the tunnel and from the tunnel spoil, representing seven genera (*Batrachopus*, *Anchisauripus*, *Gigandipus*, *Eubrontes*, *Grallator*, *Triænopus*, and *Shepardia*) and thirteen species, including one new species and one new subspecies, representing parasuchians, theropod dinosaurs, and possibly amphibians. They were both bipedal and quadrupedal forms.

This new locality extends the southward geographic range of the footprints by some 10 miles, Middlefield being hitherto the farthest southerly area where prints have been definitely found. Seven of these species are

apparently hitherto unreported from Connecticut, and nine have not been previously collected from the Triassic posterior shales, thus establishing their horizon about 1,000 feet lower in the formation than before known.

There are three horizons carrying considerable quantities of fossil wood. The black shale at the site of the dam, the tough gray sandstone at the West Portal, and the black shale, much higher, in ascending order. The first is characterized by what seems to be *Loperia*, the second by *Baiera*, while the uppermost horizon contains huge quantities of wood, but in extremely fragmentary and crushed condition. In all horizons the wood is more or less carbonized and cut by numerous transverse fractures filled by calcite, or in some cases perhaps by silica. It is wholly unlikely that these are ferns of any kind, but it is certain that they are solid stems. They must therefore indicate left-over Cordaite, or early Gymnosperm tree vegetation.

ALTERNATING OSCILLATORY MOVEMENT IN THE CHAZY AND LEVIS TROUGHS OF THE APPALACHIAN GEOSYNCLINE

BY RUDOLF RUEDEMANN

(*Abstract*)

The mapping of the Capitol District has clearly brought out the fact that a threefold, possibly a fourfold, reversal of movement took place from Lower Cambrian time to Middle Ordovician time in the two adjoining Chazy and Levis troughs of the Appalachian geosyncline, in such a fashion that the eastern trough was submerged when the western was emerged, and *vice versa*.

The cause of these alternating warpings of the troughs is seen in the interplay of the "oceanic spread" and "continental creep," two opposite forces that, acting one from the east and the other from the west, were able to affect the nearest troughs differentially.

Brief remarks were made by Mr. Charles Butts.

DETAILS IN THE EARLY HISTORY OF THE NASHVILLE DOME

BY M. G. MEHL AND WALTER F. POND

(*Abstract*)

The Nashville Dome of Central Tennessee seems to have had an early history similar in the main to that of the Cincinnati arch as a whole. Although there is evidence of several slight emergences and deformation of the dome area in Mohawkian and Cincinnatian times, the first pronounced elevation came at the end of the Fernvale, Richmond. At that time the dome must have had an elevation of several hundred feet. The excavation of canyons to a depth of 150 feet or more about its southeastern margin in Lincoln County, Tennessee, is an evidence of this. Following a Mid-Silurian submergence, during which there were deposited on the deeply eroded surface between 300 and 400 feet of sand, clay, and lime, there was another marked elevation of the southeast side of the dome. In Lincoln County the Chattanooga formation rests on a peneplaned surface that involves late Ordovician and completely truncated, thick, Silurian series.

Read by title in the absence of the authors.

DEVONIAN STRATA IN WESTERN TEXAS

BY NELSON H. DARTON [1]

(*Abstract*)

During the past summer Devonian fossils were discovered in black shale on the west slope of Franklin Mountains at a point 12 miles north of El Paso, the first organic remains of that age reported in Texas. It has been suggested that the Caballos novaculite exposed in the Marathon uplift may be of Devonian age, but no fossils have been obtained from it.

The locality which yielded the Devonian fossils on Franklin Mountains is 5½ miles east by 1½ miles north of Canutillo station. At this place the west-dipping succession overlying the typical Fusselman limestone, which forms the higher west slope and crest of Franklin Mountains, comprises the following strata:

Section on middle west Slope of Franklin Mountains, 12 Miles north of El Paso

	Feet
1. Limestone, moderately thick bedded, dark gray	500 or more
2. Limestone, some chert, cup corals and *Chætetes milleporaceous*	50
3. Shale, greenish drab, sandy, with nodular buff limestone layers	170
4. Limestone, gray, with large lenses of bluish and brownish chert; some interbedded brown sandstone	210 ±
5. Limestone, dense, dark, weathering bluish, with thin laminæ	33
6. Limestone, dark gray, with thin chert layers, brown to buff, and 3-foot chert layer at base. Fossils not determined	123
7. Limestone, dense, bluish, weathers gray, slabby	60
8. Shale of dark color, largely covered, containing near base black limestone weathering buff or gray, with fossils	105
9. Brown and black chert with some interbedded dense limestone	56
10. Covered; evidently shaly; on heavy ledges of typical Fusselman limestone	13

Not far above these strata, but apparently separated by a fault, are limestones containing Permian fossils.

This section was measured by Phillip King and Robert King, who accompanied me on the trip, and collected fossils from bed number 2, which they regard as representing the base of the Strawn, a formation of the Pennsylvanian succession, exposed in Hueco Mountains, 20 miles east. Bed number 8 has many characteristics of the Percha shale as exposed in the San Andres, Sacramento, and other ranges not far north in New Mexico. The fossils collected from the lower hard layers were examined by Dr. Edwin Kirk, of the United States Geological Survey, who found they comprised an *Orbiculoidea* sp. *Lingula* sp. and fragments of a large pelecypod "probably of Upper Devonian age (Percha shale horizon)." It is suggested by my companions that the cherty strata overlying these black shales may represent the Helms group

[1] Presented by permission of Director of the U. S. Geological Survey.

of Beede, of upper Mississippian age, or even a greater range of earlier Carboniferous time. The outcrop zone of these strata is very narrow, but may extend some distance north. They are cut off by faulting to the south.

Reference should here be made to the very accurate mapping of the complicated geology of the Franklin Mountains by G. B. Richardson in the El Paso Folio. He also established a most useful classification of the lower Paleozoic strata of the region.

Read by title.

TEXAS EOCENE: CORRECTIONS

BY GEORGE HALCOTT CHADWICK

(*Abstract*)

(1) Midway of Medina County, Texas. The State Survey bulletin on this county subdivides the Midway beds into the Elstone and Squirrel Creek formations, in ascending order. Extended field-work has shown that these subdivisions have been inverted, the Elstone actually being the higher, and that, in consequence, the two have been badly confused; also that there is possibly a third member locally present above the Elstone glauconitic limestone.

(2) Carrizo-Wilcox contact. In the same bulletin the Carrizo sandstone is described and mapped as highly transgressive across the Wilcox beds, but all of the occurrences so claimed have proved to be either Reynosa (Uvalde) beds or plain *caliché*. Since this asserted unconformity has proved disconcerting to classification and has been widely quoted, the correction is an important one.

Read by title.

NEW FAMILY OF SOUTH AMERICAN PLIOCENE MAMMALS

BY ELMER S. RIGGS

(*Abstract*)

Specimens of flesh-eating mammals collected by the Field Museum paleontological expeditions from the Araucanean formation of northern Argentina reveal the presence in that formation of fossil marsupial carnivores of unique characteristics. These animals are distinguished by the presence of a strong, trenchant, upper canine tooth comparable to that of the sabre-tooth tigers. A corresponding flange appears on the mandible for the protection of this tooth. The incisor teeth are absent both above and below; the premolars are reduced in size and in number; the molars retain a primitive marsupial character similar to that of Borhyæna. The nasal bones have no contact with the frontals. The maxillaries are backwardly extended; the orbits are entirely enclosed in a bony ring.

A well-preserved skull and mandible showing the entire dental series, together with the other characteristics enumerated above, were exhibited. A full description of these fossils may be expected to appear in an early issue of the Field Museum publication.

At this point the session adjourned.

ANNUAL DINNER

Four hundred Fellows and friends of the Society, including members of the affiliated and associated societies, assembled at the Hotel Astor for the Annual Dinner. This was by far the largest attendance in the history of the Society.

PRESENTATION OF THE PENROSE MEDAL

Past President Frank D. Adams, in presenting Jakob Johannes Sederholm, Director of the Geological Survey of Finland, for the Penrose Medal, spoke first of certain geologists of the past century who had read in the rocky strata of the earth, especially in England, the records of what might be called the medieval and modern periods of the history of the earth.

He called attention to the fact that for the history of still earlier times we are indebted to the labors of the geologists of North America and of Finland. Among those who had worked in the latter country Doctor Sederholm stood out preeminent. He had discovered and deciphered the records of at least five successive series of Precambrian rocks, which carried back the history of the world to near the beginning of geological time.

He mentioned also Doctor Sederholm's attainments in other departments of learning, as well as the brilliant services which he had rendered to his country in the field of diplomacy.

In voting to him the Penrose Medal, the Geological Society of America regarded him as one of the foremost geologists of the present day.

RESPONSE BY J. J. SEDERHOLM

MR. PRESIDENT, DR. ADAMS, LADIES AND GENTLEMEN:

I find it hard to express in any adequate way my feelings of gratitude for the friendship invariably extended to me by my American colleagues, culminating now in this honor which the Geological Society of America has conferred on me by the award of the Penrose Medal.

The more than kind words which the President and Dr. Adams have spoken add still more to that honor. There could be no man more competent than Dr. Adams to give a verdict, with the full authority of experience and wisdom, on matters relating to Precambrian geology. However, I fear that my colleague has failed in this particular case to show his wonted perfect freedom from bias and has let friendship influence his judgment in my favor. This circumstance, however, only gives his words greater value to me personally.

The present situation reminds me of a naïve question which was asked of a friend of mine in Finland. A gentleman said to him: "I think I have noticed that geologists are more often publicly mentioned in complimentary terms than other naturalists. When a geologist arrives from abroad he is usually referred to as the 'celebrated' or the 'famous geologist.' Are there really so many prominent geologists? If it is so, can you tell me why they are comparatively so numerous?"

My friend, being a scientist, could give no definite answer. I have gradually evolved a theory. Geologists are international folk, working in close comradeship, and they often have a generous appreciation of each others' merits, sometimes even when the other man has opinions contrary to their own—opinions which are, of course, entirely wrong.

I owe to the friendship and comradeship of American and Canadian geologists the feeling I have long had of being almost at home on this great western continent, and I owe to their generosity of feeling the award of the Penrose Medal, which has recently been given to such a man as Thomas Chrowder Chamberlin. It is an honor of which any scientist might well be proud.

Like Great Britain, America may be called a geologist's paradise. Sharing the advantage of an insular position, America has the further advantage, important to a geologist, of being a somewhat greater island than Great Britain, with an infinity of varying and interesting geological features. American geologists have been equal to the task given them by Nature, and have, moreover, extended their work to other continents, in that Viking spirit which is a common heritage to all northern nations. I congratulate my American colleagues on what they have achieved and am proud of having now some right to be regarded as one of them.

Geologists are international. I do not call them cosmopolitan, since I have always insisted on the proper use of terms derived from Greek. Some astronomers may perhaps feel as much at home on the planet Mars or elsewhere in the cosmos as on our own planet, Gea. To geologists, in spite of there being an astronomic geology, this little planet Gea is their only home and abode, and we may call ourselves geopolitan rather than cosmopolitan.

Moreover, each of us has a country as well, which is dearer to him than all other parts of the planet. I regard the distinction shown to me not as a recognition of my own work alone, but also of that of my collaborators in Finland, and that greater geological fatherland of mine, which we call Fenno-Scandia.

I am particularly glad to receive a medal carrying the name of Dr. Penrose, which reminds me of the important work done by him and so

many other American geologists in the field of economic geology. Modern mining derives much benefit from the work of geologists. Modern prospecting uses methods which make it entirely scientific, but scientific prospecting always remains 75 per cent geology.

The President asks me to review briefly the result of our geological work in Finland. I feel some hesitation in addressing an assembly gathered around dinner tables on such theoretical matters, although aware that I have taken part in many private dinners where geologists "talked shop" in the presence of ladies.

I will try to do it as briefly as possible.

I will not enter on any review of the *methods* which we have used and, in part, developed, for the study of the metamorphic and ultrametamorphic phenomena.

For my part, I have mainly studied the metamorphic rocks in order to discover their original features, so as to read them in the same way as we read the erased letters of a palimpsest under the later writings which have been inscribed on it. My study of the granite-injected rocks (the migmatites), which has led to results similar to those of the French school of petrology and of Lawson and other workers on this continent, has also had as its main objective a better understanding of the history of these rocks.

The classification of the Precambrian of Fenno-Scandia was worked out by a detailed study of the rocks, their contacts, and their relations to epochs of mountain-building, and later checked by a geotectonic study of the rock structures by methods borrowed from Swiss geologists.

Our stratigraphic classification, which could at one time be compared to Penelope's web—often torn and rewoven—gradually became more definite, although there is still much under dispute. However, we have arrived at some results which may be said to be in part new in principle.

The "downward progress of geology"—downward in time and in space—has continued until we can state that even among the most ancient Archean rocks there are some made by the same processes which still act today. We may even get glimpses into paleogeographic features of these very ancient worlds.

In Fenno-Scandia, at least three, possibly four, great cycles of Precambrian sedimentation exist. Each of them is separated from the next following and preceding by epochs of strong mountain-folding and subsequent deep erosion.

Especially the second last of the aforementioned great Precambrian cycles—that comprising, among others, the rocks which have been called

Jatulian and Kalevian—is of great general interest. We are able to state that these rocks possess at some places the character of well preserved sediments, of much the same type as the Huronian rocks of North America, while they are elsewhere extremely metamorphic and mixed up with granitic veins, then presenting the character common among rocks which are usually referred to as Archean. The strong mountain-building processes which followed the deposition of these sediments had an entirely modern character and were very similar to those by which the Alps have been raised; and, what is of greatest interest, we are able to state that the folding *has not been ubiquitous,* but that in these very old mountain chains—the Karelides of Carelia, in eastern Finland and the adjacent parts of Russia—areas of greater resistance have existed next to the most strongly folded portions, quite in the same way as in younger mountain chains.

It seems to me fairly probable that the same may be true also of the foldings which gave rise to the still older mountain chains, which I designate as the "Sveco-Fennides," the folds of which run with a east-northeast direction from middle Sweden over to the southern coast of Finland. These older folds are cut almost at right angles by the strike of the folds of the Karelides, running south to north or north-northwest to south-southeast.

In general, I think that the proofs of the old dogma of a ubiquitous folding in Archean time are entirely failing. This assumption is also rather improbable from a geophysical point of view. It is simply the last remaining relic of the old anti-uniformitarian conception of the Precambrian. The idea is so ingrained that I have needed the greater part of a lifetime myself to get rid of it.

If we assume that the Archean folding has not been ubiquitous, but has taken place, like the foldings of later ages, along certain limited zones of the earth's crust, then our view of the oldest formations of the earth becomes radically changed.

We used to correlate all the formations in different parts of the world which possess an "Archean" character, and in the same way thought it probable that the feebly metamorphic sediments of a character like that of the Huronian were everywhere nearly synchronous. The same argument has again been applied to the nearly horizontal sediments of Keweenawan type; but, if the movements which have affected the sedimentary deposits have not been ubiquitous, then the basis of the earlier correlation has been partly wrong, and we have to revise it, studying the geotectonic movements in order to show which may really be synchronous

and trying to find other criteria for correlation. For instance, in certain similiarities of the sediments due to climatological events which have taken place over large areas, definite phases of widespread eruptive activity, etcetera,

I still hope, as time and other conditions permit, to devote myself to a comparative study of this kind of Precambrian formations in different parts of the world. In order to be successful, it involves, however, traveling on an extensive scale; but I hope greater results from the work of a younger generation, which starts with a greater experience than its predecessor and thus represents an older and more mature science.

Since we can not even say how many cycles separated by periods of diastrophism exist among Precambrian sedimentary rocks, nor which of them may be contemporaneous in different parts of the world—still less how many sedimentary series of system rank may exist within each cycle—we have as yet no means of reaching even a preliminary estimate of the total length of Precambrian time. In any case, it seems likely that the Precambrian series comprises more cycles than the Postcambrian one. Thus the vista of the oldest parts of the history of our planet, or, more properly, over the eras which are to historical geology what archeology is to modern history, gets very much enlarged. I think we can confidently say that Precambrian geology is able to endorse any amount which paleontologists or, in general, evolutionists may draw on the bank of time.

Are there, then, among rocks from the Progonozoic eras, as I have proposed to call them—the eras of the ancestral organisms—no fossil remains of these organisms, or how do we account for their absence? I think that we have, also in the deeper Archean, if we may use that term in its old significance, phenomena which allow us to answer the first question in the affirmative. The alleged fossils, however, are scanty and poor. The sudden appearance of the rich fauna and flora in Cambrian time really gives the impression of an explosion. However, I think that we need not be so surprised that evolutionary processes should occasionally hasten their speed very suddenly; for we ourselves live in an epoch of the world's history which has seen more changes in a century than in the previous many thousand years. We witness evolution, but of an explosive character. Without that insight we do not understand our own age, nor, I am inclined to add, the ages of explosive paleontological evolution.

I have tried to emphasize the sheer immeasurable length of Precambrian time. Is, then, the Ocean of Time really, as Shelley has it, an "*unfathomable* sea whose waves are years"? Was old Hutton right when

he said that in the history of the earth we can see "no vestige of a beginning"? For my part, I am inclined to think that there are, among the oldest rocks, some indications of our nearing a beginning of the present order of things and of the existence of a primitive crust, although large parts of this granitic crust are certainly of later age. But I can not enter here on this difficult question, having already, despite my original intention, too long laid claim on your attention.

I will only say one word more in apology.

Having mainly had to do with rocks whose age is measured in figures that lie beyond a few hundred millions of years, and having tried myself to extend the geological record by many untold millions more, I fear my own philosophy begins to approach that expressed in a Finnish proverb, quoted especially by lazy people, who say that "nothing is so plentiful as time,"—*"ei ole mitään niin paljo kuin aikaa."*

AFTER-DINNER PROGRAM

OUR GROWING WORLD

"Open the Book of the Earth"

Nature, Research, Education . . . . . DR. JOHN C. MERRIAM

"Up the Grand Canyon the full morning flowed.
I heard the voices moving through the abyss, . .
With the deep sound of pine woods, league on league
Of singing boughs, each separate, each a voice,
Yet all one music."

Twenty-five Years of Geophysics . . . . . DR. ARTHUR L. DAY

"There was a time
When Etna did not burn, for all things change;
And mightier things by far have changed than these,
In the slow lapse of never-ending time."

Astronomy and Geology . . . . . DR. F. R. MOULTON

"Under the high stars man creeps, too infinitesimal to be scanned;
And, over all the worlds that dwindle away
Beyond the uttermost microscopic sight,
He towers—"

Sources of Energy . . . . . DR. R. A. MILLIKAN

"The long-sought consummation of all law,
Throughout this manifold universe, might shine clear
Enfolding Space and Time, atoms and suns,
With all the fantastic hosts of life
And all their generations

Through all worlds, in one pure
Phrase of Music,
Like a star seen in a distant sky."

"Guard the immortal fire,
Honor the glorious line of the great dead.
To the new height let all thy soul aspire;
But let those memories
Be thy wine and bread."

—ALFRED NOYES, *"The Book of Earth."*

SESSION OF SATURDAY MORNING, DECEMBER 29

The meeting was called to order by President Willis at 9 a. m., in the Duplex Assembly Room, School Service Building, and proceeded immediately to the reading of scientific papers.

TITLES AND ABSTRACTS OF PAPERS

ILLINOIAN, KANSAN, AND NEBRASKAN DRIFTS NEAR WINCHESTER, ILLINOIS

ALFRED H. BELL AND MORRIS M. LEIGHTON

(*Abstract*)

Heretofore only two glacial drifts have been known in the southern half of the State of Illinois. Recent field-work near Winchester reveals definite evidence of three glacial drifts, the youngest of which is known to be of Illinoian age; hence the two older must be respectively Kansan and Nebraskan. A pre-Illinoian valley-train deposit was also found in this area which exhibits cross-bedding to the west, suggesting that it was fed by an ice-sheet in the Labrador field. Since the exposure of the overlying till lacks about 100 feet of reaching the Illinoian upland plain, it is not possible to state whether the underlying valley-train deposit is Kansan or Nebraskan in age.

MODERN AND INTERGLACIAL WEATHERED ZONES: THEIR STRUCTURE, CONDITIONS OF DEVELOPMENT, AND USEFULNESS IN CORRELATION AND IN INTERPRETING INTERGLACIAL HISTORY

BY MORRIS M. LEIGHTON AND PAUL MACCLINTOCK

(*Abstract*)

Although for many years glacial geologists have recognized the value of old soils, leached and oxidized zones, and, in more recent years, gumbotil as criteria in distinguishing and correlating drift sheets, there have been some features of the weathered zones which have been imperfectly understood and their significance uncertainly determined.

During the past three years, in the course of making detailed examinations of modern soils and weathered zones on drift sheets and loesses of different ages and under different topographic situations, the authors, in collaboration with Messrs. Smith and Norton of the Illinois State Soil Survey have come to

recognize that there have developed different types of weathered zones, each divisible into definite subzones or horizons which carry consistently. In the case of the older drift sheets, where progressive erosion has changed the original topographic situation, a secondary type of weathered zone may be seen imposed upon the primary type which had developed under the previous set of conditions.

The paper will present in summary form (1) the basis of the divisions into types, (2) the characteristics and origin of the subzones of each type, (3) the criteria for recognizing the change of weathering cycle, and (4) the importance of recognizing these features in correlation of drift sheets and in reading interglacial history.

These two papers were presented by Doctor Leighton, and after the conclusion of the second they were briefly discussed by Messrs. Eliot Blackwelder, Andrew C. Lawson, and C. F. Marbut.

DRIFT IN KANSAS

BY WALTER H. SCHOEWE

(*Abstract*)

The glaciated area of northeastern Kansas marks the southern extension of the Kansan drift sheet. Field investigations show that erosion has greatly modified the drift plain by obliterating most of the glacial topography and by reducing the amount of the drift. The present topography is essentially bedrock controlled except for a strip of land from 6 to 10 miles wide bordering the Missouri River, where hills of maturely dissected loess characterize the surface. The drift varies in thickness in the central part of northeastern Kansas, where the till is from 30 to 100 feet thick, to less than 5 feet at the borders. Within the drift plain are numerous places where the glacial deposits are entirely wanting or are represented only by scattered erratics.

New deposits of till, both true and reworked, have been located and mapped from 6 to 15 miles south and west of the supposed glacial border. On the basis of these deposits, together with other evidence, the line marking the maximum extent of the ice-sheet in Kansas has been extended from 10 to 15 miles beyond the previously mapped glacial border.

The unaltered till is bluish gray in color, contains few pebbles and boulders, and is broken up by joints into irregular, small, polyhedral blocks. Most of the till deposits are oxidized to a depth of at least 15 feet and are light yellow to brown in color. South of Kansas River the till is oxidized to a very deep red. The weathered till is broken up by joints into large, polyhedral blocks separated by white seams of calcareous material, which are very characteristic of the till deposits of Kansas and resemble walls of rock masonry. Leaching has penetrated on the average to a depth of 10 feet.

Among the pebbles and boulders associated with the drift are quartzites, granites, gabbros, diorites, iron-bearing rocks, cherts, basalts, gneisses, schists, and local sandstones, limestones, and shales. Sioux quartzites are the most numerous and the best preserved. Most of the granites and coarse-grained basic rocks are disintegrated. The dense, igneous rocks show partial decay

and in many cases still bear striations. Where the drift is thin the cherts are weathered to a white, dull, corky material. The absence of many local sandstones and limestones in the drift is explained by the fact that the ice-sheet advanced over a bedrock surface which was predominantly shale. Boulders of quartzites and granites from 3 to 18 feet in diameter are not uncommon; at several places near the western margin of the glaciated area they occur in such profusion as to suggest at least temporary halting places for the ice-front.

Loess and loess-like material occurs almost everywhere in northeastern Kansas, but especially along the courses of the major streams, where it often attains a thickness of over 50 feet and where it usually is very sandy in its lower portion. A suggestion of two loesses is seen at places where the typical loess is underlain by a reddish, loess-like material containing small, siliceous pebbles. This reddish material may represent an older reworked loess or perhaps the end phase of a highly weathered till.

CONDITIONS OF VARVE CORRELATIONS

BY ERNST ANTEVS

(*Abstract*)

Correlation between graphs of varved late glacial clay postulates, besides, of course, good agreement, various conditions because of recurrence of climatic periods, limited variations of the thickness of the varves, etcetera. While the varved clay is an unrivaled instrument of precision, it must be used with a great amount of good judgment. The most important condition of varve correlations are:

1. The summer temperature of the regions from which the varve measurements are derived must be known to have undergone the same annual variations during the deposition of the clay; for the amount of sedimentation, the thickness of the varves was chiefly determined by the total summer temperature. Correlation is thus feasible between varve curves from the Hudson Valley and the Connecticut Valley, but is out of the question between graphs from North America and Europe.

2. The varve series to be correlated must be known to date from approximately the same time. Rough correlations must be made by means of moraines, striæ, etcetera, before detailed varve connections can be attempted.

Brief remarks were made by Dr. J. J. Sederholm.

INTERGLACIAL DEPOSIT IN CENTRAL NEW YORK

BY O. D. VON ENGELN

(*Abstract*)

In central New York evidence of two or more glacial advances in the Pleistocene consists chiefly in the presence of gorges resulting from stream erosion in interglacial time. No certain occurrence of younger over older till has been reported. Neither has anyone been able in this region to distinguish surficial glacial deposits to be of different ages. Accordingly a find of greatly weathered gravels quite surely of interglacial origin at a site

that permits understanding of the manner of their deposit and the conditions of their preservation is significant. Six Mile Creek Valley south of Ithaca, New York, is a glacially eroded trough hanging above the more deeply cut, also ice-eroded, trough of the Cayuga Valley. The bottom of the glacial Six Mile trough is trenched by interglacial and postglacial gorges. The preservation of interglacial gorges indicates relative erosive incompetence on part of the later ice advance. At the site of an interglacial waterfall flutings were developed in massive sandstone bedrock by the erosion of swift stream currents. The orientation of these flutings permitted the accumulation and preservation in their hollows of interglacial stream detritus laid down as delta deposits in a lake with rising water level, ponded in front of the ice of the last advance. These interglacial gravels are much weathered, the bedrock flutings in which the gravels are deposited are in quite fresh rock; gravels deposited in lakes fronting the retreating ice of the last advance are practically unweathered. It is suggested that if two or more sets of interglacial gorges are present in central New York, as other observers urge, till from the earlier ice advances should have been preserved very commonly in the more ancient gorges. If, however, as here argued, the interglacial gorges are all of the same age, they were rock cuts made just preceding the last ice advance and the only interglacial deposits they can contain will be stream gravels in their bottoms or at special sites as described above.

Samples of the two types of gravels were shown.

GLACIAL HISTORY OF THE EAST SIDE OF THE SIERRA NEVADA

BY ELIOT BLACKWELDER

(*Abstract*)

A study of the Pleistocene moraines shows that a sequence of three and probably four distinct epochs of glaciation can be recognized. The moraines of the fourth or youngest stage are but little affected by weathering and erosion. Those of the third epoch have been notably weathered and eroded in detail, but are still mappable and recognizable as moraines. The second epoch is represented by extensive bodies of unmistakable till that have been so deeply and maturely eroded that nearly all morainic topography has been destroyed, but the till was deposited after the major topographic features of the range had been formed. The first epoch is indicated by isolated remnants of bouldery till-like material that lie on high divides and isolated mountains, where the deposit could have been made only before the mountains attained their present relief and their deep canyons. These deposits contain boulders over 20 feet long, but they are so decayed that glacial scratches have not yet been found on them.

Interesting relations between the volcanic and general physiographic history of the region on the one hand and the several glacial stages on the other have been worked out. The dry eastern slope of the range is especially favorable for glaciologic study because the landscape is but little obscured by forests.

Brief remarks were made by Messrs. F. E. Matthes and Bailey Willis.

LATE GLACIAL HISTORY OF THE NASHUA VALLEY, IN CENTRAL MASSACHUSETTS

BY THOMAS CLACHAR BROWN

(Abstract)

The northward retreat of the lobe of ice which occupied the Nashua Valley, in central Massachusetts, uncovered a succession of basins in which lakes developed. Deltas and sand plains deposited in these lakes indicate their elevation and outline. During the early stages of this development the north branch and the south branch of the Nashua were independent, but during the later stages they were united and developed as a unit. This paper outlines the different lake areas and notes the characteristics and peculiarities of the different lake deposits.

FOLSOM CULTURE AND ITS AGE

BY BARNUM BROWN

(Abstract)

Three years of excavation has been completed near the village of Folsom, New Mexico, where from 40 to 50 skeletons of an extinct species of buffalo, remains of an ancient meat kill, were found on a former stream course, and with them 16 arrows of distinctive type.

The overlying sediments were highly restratified earth of a nature that indicates great antiquity, dating back to the close of the Pleistocene.

DISCUSSION

KIRK BRYAN: Through the courtesy of Mr. Brown and the American Museum, Mr. Neil M. Judd and I, as representatives of the Smithsonian Institution, had the privilege of inspecting the Folsom deposits this past summer. There is no question as to the association of the beautifully made implements with the bison bones. Both occur in undisturbed ground and there is no possibility of intrusion; so that the conclusion must be accepted that *Bison taylori* and the men who made the spear points were contemporaneous. The apt and penetrating conclusions of Mr. Brown, derived from the arrangement of the bones, appear to me to be sound. The deposits are the clayey valley fill of a very small valley, locally called Dead Horse Gulch. They contain small lenses of dirty gravel derived from the thin sandstone plates in the local Cretaceous shale. Except for the limy concretions, the deposit is similar to other Recent deposits in similar situations. Limy concretions of smaller size do, however, occur in the Recent deposits in the Zuñi drainage and doubtless elsewhere in New Mexico.

The lava flows of Johnson Mesa rest in a smooth erosion surface of considerable antiquity. The stream system to which Dead Horse Gulch belongs developed a broad, open valley on the east side of the mesa. Remnants of this valley level form spurs and benches 150 to 200 feet above present stream grades. The local baselevel was lowered and the streams cut a new valley below the level of the number 1 bench. At this time lava from Mount Roberts, to the south, flowed down into the valley, covering remnants of the number 1

bench and filling the inner valley. This lava dam has since been cut through, but any lake that may have formed was evanescent. The spurs and terraces of the number 2 bench lie 50 to 100 feet above the present stream grades. Again baselevel was lowered and a third valley floor developed about 30 feet above present stream grades. A local basalt eruption took place and lava poured from a terrace remnant of the number 2 bench down onto the number 3 bench. With the fourth lowering of baselevel the present inner valley was cut. Everywhere this inner valley has a broad floodplain. It was recently abandoned and the streams flow in narrow, steep-walled gulches, or arroyos, 10 to 20 feet deep. This last cycle of erosion has apparently just reached Dead Horse Gulch. If one follows this floodplain upstream, he passes without break onto the surface of the deposits containing *B. taylori;* yet downstream these deposits are loose, friable, and seem no different from those in other parts of New Mexico which contain the relics of the Pueblo culture, and must be Recent in Age. Obviously, in the headwater area of a stream system an earlier valley fill might be preserved while several cycles of erosion and sedimentation took place downstream. The material in Dead Horse Gulch is younger than the terraces, numbers 1, 2, and 3, which are doubtless Pleistocene. The time necessary to form the successive valleys represented by the "benches" should account for most of Pleistocene time. On the physiographic evidence, therefore, the age of the material containing *B. taylori* and the implements must be late Pleistocene or perhaps early Recent.

It is unfortunate that at such an important locality the physiographic evidence is not more critical, but the result thus attained appears to agree reasonably well with the paleontologic argument of Mr. Brown.

LAKE LAHONTAN

BY J CLAUDE JONES

(*Abstract*)

In Publication Number 352, Carnegie Institute of Washington, Jones and Antevs recorded recent observations in the basin of Lake Lahontan which agreed substantially as to field data, but differed radically as to the interpretation of the age and duration of the ancient lake. Jones believed the lake had existed during the past 2,000 years, while Antevs followed Russell in considering the lake as contemporaneous with the Pleistocene glaciation. The problem is further complicated by the presence of several large mammals in the Lahontan fauna that are now extinct and believed to be of Pleistocene age.

Further study has shown that the deposits and abandoned shorelines of Lake Lahontan were largely formed during the last three stages of a long series of lakes that have occupied the valleys of western Nevada during the Pleistocene; that the salts deposited by a desiccated lake became profoundly changed in character through base exchange in the clays that cover them and this change can be used to test the determination of the age of the present remnants of Lake Lahontan; that Walker Lake became a part of Lake Lahontan about 1000 A. D. and that extinct elephants, horses, and camels were living in western Nevada at this time.

GEOLOGIC CRITERIA SUGGESTING ANCIENT CLIMATIC CONDITIONS AND THEIR EVALUATION

BY GEORGE D. HUBBARD

(*Abstract*)

The paper gathers for brief discussion some fifteen or eighteen geologic and biologic criteria by which men are accustomed to estimate the climatic conditions existing at specific geologic times. It then tries to put them in order of importance and of exactness with some discussion of reasons for values given. Discussion and suggestions are requested.

Brief remarks were made by Prof. Kirk Bryan.

PLEISTOCENE FORMATIONS AT BERMUDA

BY ROBERT W. SAYLES

(*Abstract*)

While in Bermuda, in 1923, the writer conceived the idea that the eolian formations and fossil soils found there might have formed as a result of glacial control of sealevel during the Pleistocene period. In 1924, accompanied by T. H. Clark, the writer found three distinct soils. In 1926 the writer and Clark found a fourth, or uppermost, soil in many places, and Clark found all four soils visible in one section at McGalls Bay. In 1928 the writer, accompanied by K. F. Mather, found a soil at Stokes Point lower stratigraphically than any of the others, and also marine limestone of Walsingham age about 25 feet above sealevel. About 125 soil outcrops have been found at this writing.

The main results of this research so far accomplished are as follows:

The chemistry of the soils in 1924 by Miss Helen E. Vassar.

The petrological examination of the soils by Larsen.

A study of the mollusca of the soils by T. H. Clark.

A study of the foraminifera of the soils by Cushman and Lothrop Bartlett.

A study of the algæ of the soils by Howe.

The writer has spent most of his time on the general geology of the problem and the structural relations of the eolianites and soils. All of the above work is of a preliminary nature.

The proof of several long periods, measured in hundreds of thousands of years, when soil formation and much erosion took place, separated by several periods of widespread dune formation of long duration, when soil formation was a negligible factor, is assured. Although glacial control of sealevel is advocated to explain best these alternating conditions, the question of isostatic readjustments necessarily involved in the glacial control theory has not been neglected.

Brief remarks were made by Dr. H. M. Ami.

KEEWATIN-TIMISKAMING BOUNDARY

BY E. S. MOORE

(*Abstract*)

In a recent article Gregory and Barrett state that the Timiskaming and Keewatin are either entirely or approximately contemporaneous. It is shown, however, that in every area where the Timiskaming series is found there is at least an important erosional unconformity indicated by a basal conglomerate containing pebbles and boulders of the Keewatin formations and also of granite which is regarded as Laurentian and which is not exposed in many of the areas studied. The later Algoman granite appears to have been injected into many of the anticlines in the Keewatin that the Laurentian granite followed and it destroyed much of the previously existing Laurentian.

STRATIGRAPHY AND PALEONTOLOGY OF THE KINDERHOOKIAN OF MISSOURI

BY E. B. BRANSON

(*Abstract*)

A preliminary statement of some of the results of ten years' investigation on the Kinderhookian of Missouri. The finished work will be ready for publication in June, 1929. Every Kinderhookian species from Missouri is figured and most figures were made from the types. The work has been carried on under the auspices of the Missouri Bureau of Geology and Mines. James S. Williams has written the part on the Louisiana limestone, I. A. Keyte the part on the Crinoidea, and Raymond Peck the part on the Blastoidea.

CORRELATION CHART OF MISSOURI FORMATIONS

BY E. B. BRANSON AND CARL C. BRANSON

(*Abstract*)

A chart showing correlation of all of the formations in Missouri. Accompanying the chart is a discussion of obsolete names and reasons for various correlations.

APPALACHIAN STUDIES I

BY DOUGLAS JOHNSON

(*Abstract*)

Studies of the New England upland peneplain by means of more than 200 projected profiles indicate that the upland surface is more complex than has generally been supposed. It consists of a number of facets of different origin, each with its own angle and direction of slope. These facets have been largely destroyed by subsequent erosion, but the method of profiling adopted permits us to reconstruct their positions and even to photograph them.

A large part of the Western Upland is a plane sloping southeast approximately 40 feet per mile, an angle so steep that if the plane be projected out across the Connecticut Valley, it does not connect with any plane of the Central Upland, but plunges down to intersect the floor of the Connecticut Valley

or the eastern wall of that valley near its base. This inclined plane intersects the pre-Triassic surface at an oblique angle. The northern part of the Central Upland represents a plane which either closely approximates horizontality or slopes faintly toward the south; but the south-central part shows several facets, or a single facet broken or warped into segments, having a southeasterly inclination toward the Quinebaug Valley. Similar features are found in the Eastern Uplands.

The New England Upland as a whole thus presents the appearance of a series of tilted earth blocks, with the upper surfaces of the blocks inclined prevailingly toward the southeast at such angles that in no case can the surface of one block be projected to correlate with the surface of a neighboring block.

The surfaces thus far described are intersected by others differently oriented. One is the well-known southward sloping pre-Cretaceous peneplain. Farther north similar surfaces similarly inclined reappear at the foot of fairly distinct north- or northwest-facing scarps, as would be the case if this peneplain were repeated by faulting or flexing.

The facts set forth point toward the interpretation of the New England Upland as a complex surface consisting in some parts of a differentially upwarped and possibly flexed or faulted peneplain of comparatively recent age; and in some parts of the resurrected surfaces of more than one ancient peneplain which prior to exposure by erosion were displaced by tectonic movements.

Read by title.

APPALACHIAN STUDIES II

BY DOUGLAS JOHNSON AND KARL VER STEEG

(*Abstract*)

The theory that the southeast-flowing lower courses of the Connecticut and certain other rivers of the Northern Appalachians have been superposed from an overlapping coastal plain cover is reexamined in the light of present knowledge that the upland peneplain intersects the older and more steeply inclined peneplain underlying the coastal plain deposits. The points of deflection of the rivers toward the southeast do not coincide with the former inner margin of the beveled coastal plain beds. The presence of high-level, broad, shallow valleys on the upland, or Schooley peneplain, coincident with the present courses of the larger rivers is not consistent with the theory that these streams were incised in this peneplain from an immediately overlying coastal plain cover.

These and other difficulties disappear if we assume that superposition occurred in a cycle earlier than the Schooley. This would seem possible if the earlier (Jurassic) peneplain were uparched with a coastal plain cover (Cretaceous) which extended far inland, as is now generally regarded probable. Confirmation of this interpretation seems to be found in the results of profile and field studies of Appalachian ridges in Pennsylvania and New Jersey made by the junior author. For long distances on either side of water gaps and major wind gaps ridge crests representing the upper (Schooley or

Kittatinny) peneplain descend faintly toward the major stream courses, indicating that these streams were superposed in a cycle earlier than the Schooley (Kittatinny) and held their courses throughout Schooley (Kittatinny) time.

The junior author's studies of ridge crests adjacent to wind gaps and water gaps support the view that the Schooley peneplain and the Kittatinny peneplain are one and the same. Elevations of wind gaps are found to be more variable than elevations of water gaps. Since the latter do not represent any peneplain level, there would seem to be some doubt as to the value of wind gaps as indicators of former peneplain levels.

Read by title.

VARVES AND DURATION OF THE EOCENE EPOCH

BY WILMOT H. BRADLEY

(*Abstract*)

The Green River formation is a series of lake beds of about Middle Eocene age which occupies two large intermontane basins, one in Colorado and Utah, the other in Wyoming. The formation averages about 2,000 feet in thickness and covers an area of more than 25,000 square miles. Many of its beds of marlstone, oil shale, and fine-grained sandstone contain varves. The dominant type consists of a pair of laminæ, one of which is richer in organic matter than the other. The varves differ in thickness from a minimum of 0.014 millimeter in the beds of richest oil shale to about 9.8 millimeters in the beds of fine-grained sandstone.

Their bipartate character is explained by the different settling rates of the two principal constituents and by postulating a more or less continuous sedimentation, with first a peak in the production of carbonates and then a peak in plankton production. Both peaks apparently occurred during the summer. The preservation of the varves suggests that the lake water was thermally stratified, and, further, that the lake may not have been more than 75 or 100 feet deep where the varved deposits accumulated.

The time value of the varves is tested first by analogy with the varves in the deposits of modern lakes, and, second, by calculation from data on present stream loads of the thickness of annual laminæ to be expected in the ancient Green River Lake.

On the basis of the varves, the Green River epoch is estimated to have lasted between 5 and 8 million years. The rate of accumulation of the fluviatile deposits above and below the Green River formation is estimated as about 3,000 years per foot. According to this estimated rate and the observed rate of accumulation of the Green River formation, the duration of the Eocene epoch is estimated as between 13 and 32 million years. The average time interval indicated by these estimates is a little less than 23 million years. This estimate agrees rather closely with other previous estimates of the duration of the Eocene epoch, based on radioactive minerals, but yet it is entirely independent of them.

Read by title.

GLACIAL FILL OF A PORTION OF THE MOHAWK VALLEY

BY JAMES H. STOLLER

(*Abstract*)

Borings made in connection with an investigation of the Schenectady city water supply show that the bed of the preglacial Mohawk near Schenectady is at an elevation of about 13 feet above present sealevel. A boring made near the left bank of the river, three miles above Schenectady, at an elevation of 236 feet above sea, penetrated 223 feet of filling of the old valley, striking sandstone at the above elevation. A boring four miles farther up the valley encountered rock at 227 feet. These and other data show that the portion of the old valley, about 12 miles in length, from the Hoffman's fault to Rexford's, three miles below Schenectady, is filled with deposits.

In preglacial times the Mohawk River had evidently eroded its bed to a level corresponding to that of the Hudson River, into which, then as now, it discharged. With the coming of the ice-sheet of the Glacial Period, and especially at the waning stage, the valley was partially filled with deposits made at the ice-front (blue clay, gravel, and boulders). With the final disappearance of ice from this portion of the valley the regional depression became occupied by static waters in which very fine sand deposits overlying blue clay were deposited by inflowing streams.

When the upper Mohawk Valley became freed of ice and the valley became the outlet of the interior lakes, deposits of coarse materials borne by powerful currents were further added to the filling of the old valley, forming the head of the delta built into Lake Albany.

Read by title.

UNDERGROUND POSITION OF THE PRECAMBRIAN IN TEXAS

BY E. H. SELLARDS

(*Abstract*)

Rocks assigned with more or less assurance to the Precambrian are found exposed in Texas in the following three areas: The Llano uplift, the Van Horn region, and the Franklin Mountains. In addition, the position of these underground rocks has been indicated by well drilling over a much larger area. In this paper the depth to the Precambrian rocks, as determined from a study of cores and other rock samples from well drilling, is recorded. From the very limited amount of the rock available in well cores and cuttings, the difficulty of distinguishing between Precambrian and later metamorphic rocks is often great, the distinction being sometimes impossible to make. In the map which accompanies the paper a distinction is indicated between localities where the rocks are definitely identified as Precambrian and other localities where the identification is in doubt. The map indicates by contour lines the depth to Precambrian over that part of the State on which information has accumulated sufficiently to justify mapping. The text is explanatory of the map.

Read by title.

WORLD'S DEEPEST WELL

BY E. H. SELLARDS AND WALDO WILLIAMS

(*Abstract*)

On the land of the University of Texas, in the Big Lake oil field, in Reagan County, Texas, a well has been recently drilled to the depth of 8,523 feet. At this depth the well is producing both oil and gas. The well is located in the Permian basin of Texas, and a careful record has been kept of the character of rock and other conditions encountered in drilling. The formations penetrated are: Cretaceous, chiefly limestones and sands; Triassic, sands and clays; Permian, red beds, including salt, potash, and anhydrite beds; Permian, dolomitic limestones; and a great series, exceeding 4,000 feet in thickness, of prevailingly black limy shales, with a limited amount of fine sand of undetermined age, probably Permian or Pennsylvanian. The well reached, at 8,523 feet, the fourth oil-and-gas producing horizon.

Read by title.

TILDEN METEORITE

BY A. B. CROOK AND O. C. FARRINGTON

(*Abstract*)

The only meteorite thus far found in Illinois is one which fell at Tilden, 45 miles southeast of Saint Louis, about noon, July 13, 1927. Portions of this fall are now in the Illinois State Museum, the Field Museum, the National Museum, and Iowa State University.

An account of the fall, description of the meteorite, and its chemical and mineralogical composition are given, together with maps and photographs.

Read by title.

EVIDENCES OF MULTIPLE GLACIATION IN THE YOSEMITE REGION

BY FRANÇOIS E. MATTHES

(*Abstract*)

The detailed survey of moraines and other glacial deposits which the author made in the Yosemite region in 1913-1914 led, as has been set forth in a previous paper, to the definite recognition of two distinct stages of glaciation—a relatively late stage, recorded in a series of well preserved moraines, and an earlier stage, recorded in a series of mostly ill preserved, obscure moraines of much greater age.

The survey, however, also revealed the presence in several localities of scattered erratic boulders situated at levels considerably above the highest lateral moraines of the older series. Even in 1913 the author surmised that these erratics might indicate a third and still earlier glaciation, but conclusive proof remained lacking.

Revisits to the localities in question in 1927 have permitted the author to make further and more critical examinations, and as a result there is now

little doubt in his mind that the erratics, all of which are composed of siliceous and extremely durable rocks, are indeed the remnants of once continuous moraines of much greater antiquity than those previously referred to as "older." Accordingly, there appears to be in the Yosemite region satisfactory proof of three distinct stages of glaciation comparable in point of age and duration to those recognized in the north central parts of the continent.

For the latest stage, which corresponds in all likelihood to the Wisconsin, the name Yosemite stage seems appropriate, as the Yosemite Glacier of that stage ended within the Yosemite Valley. For the next earlier stage, which appears comparable to the Illinoian, the name El Portal stage is proposed, and for the earliest stage the name Glacier Point stage is proposed.

In addition to these major subdivisions of the Pleistocene in the Yosemite region, two stadia within the latest, or Yosemite, stage appear to be indicated by the moraines. Of these the earliest may possibly be intermediate in age between the maxima of the Yosemite and El Portal stages and may therefore be found to correspond to the Iowan.

Read by title.

RESOLUTION OF THANKS

The following resolution of thanks was offered by Chairman Bailey Willis and unanimously adopted:

The Fellows of the Geological Society of America express, with earnest appreciation, their thanks for the hospitality extended to them by the authorities of the American Museum of Natural History and the sponsors of the assembly of the American Association for the Advancement of Science; and they desire especially to thank Dr. Henry Fairfield Osborn, President of the Museum and of the Association, for his cordial and effective cooperation in making arrangements for and promoting the success of the meetings.

President Willis then announced that the business, the scientific sessions, and other activities of the annual meeting of 1928 had been completed, and on motion the forty-first annual meeting adjourned at 1:20 o'clock.

CHARLES P. BERKEY,
Secretary.

Register of the New York Meeting

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Jakob Johannes Sederholm

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Harold L. Alling
Henry M. Ami
Ernst Antevs
George H. Ashley
W. W. Atwood
H. Foster Bain
Sydney H. Ball
Florence Bascom
R. S. Bassler
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Alan M. Bateman
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Edgar T. Wherry
David White
H. P. Whitlock
George R. Wieland
Bailey Willis
Joseph E. Woodman
William E. Wrather

FELLOWS-ELECT

Horace N. Coryell
George I. Finlay
Philip G. B. Gilbert
Arthur L. Parsons
Arthur M. Piper
Allyn C. Swinnerton
David G. Thompson

In addition to the foregoing, there were registered at the meeting 501 members of affiliated and associated societies and visitors, making a total of 722.

Lists of Former Officers and Meetings, with Dates

By recommendation of the Council, a complete list of past officers, with the dates of their services, is printed in the Proceedings.

The Geological Society of America

PRESIDENTS

1889.	James Hall	1909.	Grove K. Gilbert
1890.	James D. Dana	1910.	Arnold Hague
1891.	Alexander Winchell	1911.	William M. Davis
1892.	G. K. Gilbert	1912.	H. L. Fairchild
1893.	J. William Dawson	1913.	Eugene A. Smith
1894.	T. C. Chamberlin	1914.	George F. Becher
1895.	N. S. Shaler	1915.	Arthur P. Coleman
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1897.	Edward Orton	1917.	Frank D. Adams
1898.	J. J. Stevenson	1918.	Whitman Cross
1899.	B. K. Emerson	1919.	J. C. Merriam
1900.	G. M. Dawson	1920.	I. C. White
1901.	C. D. Walcott	1921.	James F. Kemp
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1903.	S. F. Emmons	1923.	David White
1904.	J. C. Branner	1924.	Waldemar Lindgren
1905.	Raphael Pumpelly	1925.	William B. Scott
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1907.	C. R. Van Hise	1927.	Arthur Keith
1908.	Samuel Calvin	1928.	Bailey Willis

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(Not including ex-officio Vice-Presidents representing the affiliated Societies)

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1890.	J. S. Newberry	A. Winchell
1891.	G. K. Gilbert	T. C. Chamberlin
1892.	J. W. Dawson	T. C. Chamberlin
1893.	T. C. Chamberlin	J. J. Stevenson
1894.	N. S. Shaler	G. H. Williams
1895.	Joseph Le Conte	Charles H. Hitchcock
1896.	Charles H. Hitchcock	Edward Orton
1897.	J. J. Stevenson	B. K. Emerson
1898.	B. K. Emerson	G. M. Dawson
1899.	G. M. Dawson	C. D. Walcott
1900.	C. D. Walcott	N. H. Winchell
1901.	N. H. Winchell	S. F. Emmons
1902.	S. F. Emmons	J. C. Branner
1903.	Arnold Hague	H. S. Williams
1904.	H. S. Williams	Samuel Calvin
1905.	Samuel Calvin	W. M. Davis

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1908.	George F. Becker	A. C. Lawson
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1910.	Charles Schuchert	A. P. Low
1911.	William North Rice	
1912.	Israel C. White	
1913.	James F. Kemp	R. D. Salisbury
1914.	Waldemar Lindgren	Horace B. Patton
1915.	L. V. Pirsson	H. P. Cushing
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1917.	A. C. Lawson	W. D. Matthew
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1920.	George P. Merrill	W. G. Miller
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1925.	Reginald W. Brock	Marius R. Campbell
1926.	Heinrich Ries	Lewis G. Westgate
1927.	Charles K. Leith	Douglas W. Johnson
1928.	Alfred C. Lane	William H. Collins

TREASURERS

1889-1891.	H. W. Williams
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1917-	E. B. Mathews

SECRETARIES

1889-1890.	John J. Stevenson
1891-1906.	H. L. Fairchild
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1923-	Charles P. Berkey

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1925.	U. S. Grant	Florence Bascom
1926.	Nelson H. Darton	George H. Ashley
1927.	H. Foster Bain	Henry B. Kummel
1928.	George R. Mansfield	William E. Wrather

ANNUAL AND SEMI-ANNUAL MEETING PLACES

1888. Ithaca, New York.
1889. Toronto, Canada, August.
New York City, December.
1890. Indianapolis, Indiana, August.
Washington, D. C., December.
1891. Washington, D. C., August.
Columbus, Ohio, December.
1892. Rochester, New York, August.
Ottawa, Canada, December.
1893. Madison, Wisconsin, August.
Boston, Massachusetts, December.
1894. Brooklyn, New York, August.
Baltimore, Maryland, December.
1895. Springfield, Massachusetts, August
Philadelphia, Pennsylvania, December.
1896. Buffalo, New York, August.
Washington, D. C., December.

1897. Detroit, Michigan, August.
Montreal, Canada, December.
1898. Boston, Massachusetts, August.
New York City, December.
1899. Columbus, Ohio, August.
Washington, D. C., December.
1900. New York City, June.
Albany, New York, December.
1901. Denver, Colorado, August.
Rochester, New York, December.
1902. Pittsburgh, Pennsylvania, July.
Washington, D. C., December.
1903. St. Louis, Missouri, December.
1904. Philadelphia, Pennsylvania, December.
1905. Ottawa, Canada, December.
1906. New York City, December.
1907. Albuquerque, New Mexico, December.
1908. Baltimore, Maryland, December.
1909. Cambridge and Boston, Massachusetts, December.
1910. Pittsburgh, Pennsylvania, December.
1911. Washington, D. C., December.
1912. New Haven, Connecticut, December.
1913. Princeton, New Jersey, December.
1914. Philadelphia, Pennsylvania, December.
1915. Leland Stanford, Jr., University, California, August.
Washington, D. C., December.
1916. Albany, New York, December.
1917. St. Louis, Missouri, December.
1918. Baltimore, Maryland, December.
1919. Boston, Massachusetts, December.
1920. Chicago, Illinois, December.
1921. Amherst, Massachusetts, December.
1922. Ann Arbor, Michigan, December.
1923. Washington, D. C., December.
1924. Ithaca, New York, December.
1925. New Haven, Connecticut, December.
1926. Madison, Wisconsin, December.
1927. Cleveland, Ohio, December.
1928. New York City, December.

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HEINRICH RIES, Ithaca, N. Y.

Vice-Presidents:

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Treasurer:

EDWARD B. MATHEWS, Baltimore, Md.

Editor:

JOSEPH STANLEY-BROWN, 151 Quentin Street, Kew Gardens, L. I.

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WILLIAM E. WRATHER, Dallas, Texas.

(Term expires 1931)

HERDMAN F. CLELAND, Williamstown, Mass.
ELWOOD S. MOORE, Toronto, Canada.

MEMBERSHIP, 1928

CORRESPONDENTS

BARROIS, CHARLES, Lille, France. Dec., 1909.
BATHER, FRANCIS ARTHUR, London, England. Dec., 1926.
BRÖGGER, W. C., Christiania, Norway. Dec., 1909.
DAVID, SIR TANNATT WILLIAM EDGEWORTH, Sidney, New South Wales, Dec., 1923.
DE GEER, BARON GERHARD, Stockholm, Sweden. Dec., 1910.
DE MARGERIE, EMMANUEL, Strasbourg, Alsace, France. Dec., 1921.
FLETT, SIR JOHN SMITH, London, England. Dec., 1928.
HARKER, ALFRED, Cambridge, England. Dec., 1924.
HEIM, ALBERT, Zurich, Switzerland. Dec., 1909.
KIAER, JOHAN, Christiania, Norway. Dec., 1925.
KOTO, BUNJIRO, Tokyo, Japan. Dec., 1923.
LACROIX, FRANCOIS ANTOINE ALFRED, Paris, France. Dec., 1923.
LOEWINSON-LESSING, FRANZ J., Leningrad, Russia. Dec., 1926.
MOLENGRAAFF, GUSTAAF ADOLF FREDERIK, Delft, Holland. Dec., 1923.
ROGERS, ARTHUR WILLIAM, Cape Town, South Africa. Dec., 1924.
SOLLAS, WILLIAM JOHNSON, Oxford, England. Dec., 1925.
SEDERHOLM, JAKOB JOHANNES, Helsingfors, Finland. Dec., 1923.
TERMIER, PIERRE MARIE, Paris, France. Dec., 1928.
TIETZE, EMIL, Vienna, Austria. Dec., 1910.
VOGT, J. H. L., Christiania, Norway. Dec., 1925.
WALTHER, JOHANNES, Halle-Wittenberg, Germany. Dec., 1926.
WOODWARD, SIR ARTHUR SMITH, London, England. Dec., 1923.

FELLOWS

* Indicates Original Fellows (see article III of Constitution)

ABBE, CLEVELAND, JR., 123 N. Quarry St., Ithaca, N. Y. August, 1899.
ADAMS, FRANK DAWSON, McGill University, Montreal, Canada. Dec., 1889.
ADAMS, GEORGE I., University of Alabama, Tuscaloosa, Ala. Dec., 1902.
ADAMS, LEASON, H., Geophysical Laboratory, Washington, D. C. Dec., 1922.
ADKINS, WALTER S., University of Texas, Austin, Texas. Dec., 1921.
ALCOCK, F. J., Geological Survey of Canada, Ottawa, Canada. Dec., 1920.
ALDEN, WILLIAM C., U. S. Geological Survey, Washington, D. C. Dec., 1909.
ALDRICH, HENRY R., State Geological and Natural History Survey, Madison, Wis. Dec., 1927.
ALDRICH, TRUMAN H., 1026 Glen Iris Ave., Birmingham, Ala. May, 1889.
ALLAN, JOHN A., University of Alberta, Edmonton, Alberta, Canada. Dec., 1914.
ALLEN, EUGENE T., Geophysical Laboratory, Washington, D. C. Dec., 1922.
ALLEN, R. C., 1202 Hanna Bldg., Cleveland, Ohio. Dec., 1911.
ALLING, H. L., University of Rochester, Rochester, N. Y. Dec., 1920.
AMI, HENRY M., Victoria Museum, Room 105, Ottawa, Canada. Dec., 1889.
ANDERSON, FRANK M., 58 Hillcrest Road, Berkeley, Calif. Dec., 1902.
ANDERSON, ROBERT V., Menlo Park, Calif. Dec., 1911.

ANDREWS, E. C., Geological Survey of New South Wales, Sydney, New South Wales, Dec., 1920.

ANTEVS, ERNST V., American Geographical Society, Broadway at 156th St. New York, N. Y.

ARNOLD, RALPH, 812 Subway Terminal Bldg., Los Angeles, Calif. Dec., 1904.

ASHLEY, GEORGE HALL, State Capitol, Harrisburg, Pa. August, 1895.

ATWOOD, WALLACE WALTER, Clark University, Worcester, Mass. Dec., 1909.

AURIN, FRITZ L., Marland Oil Co., Ponca City, Okla. Dec., 1925.

BAGG, RUFUS MATHER, JR., 7 Brokaw Place, Appleton, Wis. Dec., 1896.

BAIN, H. FOSTER, % Amer. Inst. Mining Engineers, 29 W. 39th St., New York, N. Y. Dec., 1895.

BAKER, MANLEY BENSON, School of Mining, Kingston, Ontario. Dec., 1911.

BALDWIN, S. PRENTISS, 11025 East Blvd., Cleveland, Ohio. August, 1895.

BALL, MAX WAITE, 1104 First Natl. Bank Bldg., Denver, Colo. Dec., 1924.

BALL, SYDNEY H., 26 Beaver St., New York City. Dec., 1905.

BANCROFT, JOSEPH A., McGill University, Montreal, Canada. Dec., 1914.

BARBOUR, ERWIN HINCKLEY, University of Nebraska, Lincoln, Neb. Dec., 1896.

BARRETT, LESLIE PARK, % Inter-State Iron Co., Jones & Laughlin Bldg., Pittsburgh, Pa. Dec., 1923.

BARTON, DONALD C., Petroleum Bldg., Houston, Texas. Dec., 1921.

BARTON, GEORGE H., Boston Soc. of Nat. History, Boston, Mass. Aug., 1890.

BARTSCH, PAUL, U. S. National Museum, Washington, D. C.

BASCOM, FLORENCE, U. S. Geological Survey, Washington, D. C. August, 1894.

BASSLER, RAY SMITH, U. S. National Museum, Washington, D. C. Dec., 1906.

BASTIN, EDSON S., University of Chicago, Chicago, Ill. Dec., 1909.

BATEMAN, ALAN MARA, Yale University, New Haven, Conn. Dec., 1916.

BAUER, CLYDE MAX, P. O. Box 972, Amarillo Texas. Dec., 1923.

BAYLEY, WILLIAM S., University of Illinois, Urbana, Ill. Dec., 1888.

BEAN, ERNEST F., Wisconsin Geological and Natural History Survey, Madison, Wis. Dec., 1926.

BEEDE, JOSHUA W., 507 S. Fess Ave., Bloomington, Ind. Dec., 1902.

BEEKLY, ALBERT L., 1106 Cosden Bldg., Tulsa, Okla. Dec., 1925.

BELL, WALTER A., Victoria Memorial Museum, Ottawa, Canada. Dec., 1923.

BENSON, W. N., University of Otago, Dunedin, New Zealand. Dec., 1919.

BERKEY, CHARLES P., Columbia University, New York, N. Y. August, 1901.

BERRY, EDWARD WILBER, Johns Hopkins University, Baltimore, Md. Dec., 1909.

BEVAN, ARTHUR C., University of Illinois, Urbana, Ill. Dec., 1926.

BEYER, SAMUEL WALKER, Iowa Agricultural College, Ames, Iowa. Dec., 1896.

BILLINGSLEY, PAUL, 1027 Continental Natl. Bank Bldg., Salt Lake City, Utah. Dec., 1922.

BLACKWELDER, ELIOT, Leland Stanford Jr. University, Stanford University, Calif. Dec., 1908.

BOUTWELL, JOHN M., Natl. Copper Bank, Salt Lake City, Utah. Dec., 1905.

BOWEN, CHARLES F., % Standard Oil Co., 26 Broadway, New York City. Dec., 1916.

BOWEN, N. L., Geophysical Laboratory, Washington, D. C. Dec., 1917.

BOWIE, WILLIAM, U. S. Coast and Geodetic Survey, Washington, D. C. Dec. 1919.

BOWMAN, ISAIAH, American Geographical Society, Broadway at 156th St., New York City. Dec., 1924.
BRADLEY, WILMOT, H., U. S. Geological Survey, Washington, D. C. Dec., 1927.
BRANSON, EDWIN BAYER, University of Missouri, Columbia, Mo. Dec., 1911.
BRETZ, J HARLEN, University of Chicago, Chicago, Ill. Dec., 1917.
BRIGHAM, ALBERT PERRY, Colgate University, Hamilton, N. Y. Dec., 1893.
BROCK, REGINALD W., Univ. of British Columbia, Vancouver, B. C. Dec., 1904.
BRODERICK, T. MONTEITH, Calumet and Hecla Mining Co., Calumet, Mich. Dec., 1921.
BROKAW, A. D., 157 Maplewood Ave., Maplewood, N. J. Dec., 1920.
BROWN, BARNUM, American Museum of Natural History, New York, N. Y. Dec., 1910.
BROWN, CHARLES WILSON, Brown University, Providence, R. I. Dec., 1908.
BROWN, JOHN STAFFORD, St. Joseph Lead Co., Exploration Dept., 250 Park Ave., New York, N. Y. Dec., 1922.
BROWN, THOMAS CLACHAR, Laurel Bank Farm, Fitchburg, Mass. Dec., 1915.
BRUCE, E. L., Queens University, Kingston, Ontario, Canada. Dec., 1920.
BRYAN, KIRK, U. S. Geological Survey, Washington, D. C. Dec., 1922.
BUCHER, W. H., University of Cincinnati, Cincinnati, Ohio. Dec., 1920.
BUDDINGTON, A. F., 178 Prospect Ave., Princeton, N. J. Dec., 1919.
BUEHLER, HENRY ANDREW, Rolla, Mo. Dec., 1909.
BURCHARD, E. F., U. S. Geological Survey, Washington, D. C. Dec., 1920.
BURLING, LANCASTER D., Vassar College, Poughkeepsie, N. Y. Dec., 1917.
BURWASH, EDWARD M. J., 40 Bedford Road, Toronto, Canada. Dec., 1916.
BUTLER, BERT S., U. S. Geological Survey, Golden, Colo. Dec., 1912.
BUTLER, G. MONTAGUE, College of Mines, Tucson, Arizona. Dec., 1911.
BUTTS, CHARLES, U. S. Geological Survey, Washington, D. C. Dec., 1912.
BUWALDA, J. P., Institute of Technology, Pasadena, Calif. Dec., 1920.
BYBEE, HALBERT P., Dixie Oil Co., San Angelo, Texas. Dec., 1926.
CADY, G. H., Illinois Geological Survey, Urbana, Ill. Dec., 1920.
CALHOUN, FRED HARVEY HALL, Clemson College, S. C. Dec., 1909.
CALKINS, FRANK C., U. S. Geological Survey, Washington, D. C. Dec., 1914.
CAMPBELL, HENRY D., Washington and Lee Univ., Lexington, Va. May, 1889.
CAMPBELL, MARIUS R., U. S. Geological Survey, Washington, D. C. Aug., 1892.
CAMSELL, CHARLES, Department of Mines, Ottawa, Canada. Dec., 1914.
CAPPS, STEPHEN R., JR., U. S. Geological Surv., Washington, D. C. Dec., 1911.
CARMAN, J. ERNEST, Ohio State University, Columbus, Ohio. Dec., 1917.
CARNEY, FRANK, P. O. Box 464, Fort Worth, Texas. Dec., 1908.
CASE, ERMINE C., University of Michigan, Ann Arbor, Mich. Dec., 1901.
CHADWICK, GEORGE H., 175 Bridge St., Catskill, N. Y. Dec., 1911.
CHAMBERLIN, ROLLIN T., University of Chicago, Chicago, Ill. Dec., 1913.
CHANEY, RALPH W., Carnegie Institution of Washington, Berkeley, Calif. Dec., 1926.
CLAPP, CHARLES H., State University, Missoula, Mont. Dec., 1914.
CLAPP, FREDERICK G., 50 Church St., New York City. Dec., 1905.
CLARK, BRUCE L., Bacon Hall, Univ. of California, Berkeley, Calif. Dec., 1918.
CLARK, F. R., 723 Petroleum Bldg., Tulsa, Okla. Dec., 1919.
CLARK, GLENN C., Marland Oil Co., Ponca City, Okla. Dec., 1927.
CLARK, THOMAS H., McGill University, Montreal, Canada. Dec., 1926.

CLARK, W. O., Naalehu, Kau, Hawaii. Dec., 1920.
CLARKE, EDWARD DE COURCY, University of Western Australia, Perth, Western Australia. Dec., 1924.
CLELAND, HERDMAN F., Williams College, Williamstown, Mass. Dec., 1905.
CLEMENTS, J. MORGAN, 20 Broad St., New York City. Dec., 1894.
COBB, COLLIER, University of North Carolina, Chapel Hill, N. C. Dec., 1894.
COLEMAN, ARTHUR P., Toronto University, Toronto, Canada. Dec., 1896.
COLLIER, ARTHUR J., U. S. Geological Survey, Washington, D. C. June, 1902.
COLLINS, WILLIAM H., Geological Survey, Ottawa, Canada. Dec., 1921.
COLONY, ROY JED, Columbia University, New York City. Dec., 1924.
CONDIT, D. DALE, P. O. Box 916, Bakersfield, Calif. Dec., 1916.
CONDRA, GEORGE E., University of Nebraska, Lincoln, Neb. Dec., 1926.
COOK, CHARLES W., University of Michigan, Ann Arbor, Mich. Dec., 1915.
COOKE, C. WYTHE, U. S. Geological Survey, Washington, D. C. Dec., 1918.
CORBETT, CLIFTON S., % Gulf Oil Cos., 21 State St., New York, N. Y. Dec., 1925.
CORYELL, HORACE NOBLE, Columbia University, New York, N. Y. Dec., 1928.
COSTE, EUGENE, 410 Royal Bank Bldg., Toronto, Canada. Dec., 1906.
COTTON, LEO ARTHUR, University of Sydney, Sydney, Australia. Dec., 1924.
CRAWFORD, RALPH DIXON, 1050 Tenth St., Boulder, Colo. Dec., 1916.
CROOK, ALJA R., State Museum of Natural History, Springfield, Ill. Dec., 1898.
CROSS, WHITMAN, 101 East Kirke St., Chevy Chase, Md. May, 1889.
CULVER, GARRY E., 310 Center Ave., Stevens Point, Wis. Dec., 1891.
CULVER, HAROLD E., State College, Pullman, Wash. Dec., 1925.
CUMINGS, EDGAR R., Indiana University, Bloomington, Ind. August, 1901.
CUSHMAN, J. A., Sharon, Mass. Dec., 1919.
DAKE, C. L., Missouri School of Mines, Rolla, Mo. Dec., 1920.
DALE, N. C., Hamilton College, Clinton, N. Y. Dec., 1920.
DALY, REGINALD A., Harvard University, Cambridge, Mass. Dec., 1905.
DANA, EDWARD SALISBURY, 24 Hillhouse Ave., New Haven, Conn. Dec., 1908.
*DARTON, NELSON H., U. S. Geological Survey, Washington, D. C.
DAVIS, E. F., 417 E. Randolph St., Glendale, Calif. Dec., 1920.
*DAVIS, WILLIAM M., Room 402, 79 Milk St., Boston, Mass.
DAY, ARTHUR LOUIS, Geophysical Laboratory, Washington, D. C. Dec., 1909.
DECKER, CHARLES ELIJAH, University of Oklahoma, Norman, Okla. Dec., 1924.
DE GOLYER, E. L., 65 Broadway, New York City. Dec., 1918.
DEUSSEN, ALEXANDER, 1917 Post-Dispatch Bldg., Houston, Texas. Dec., 1916.
DE WOLF, FRANK WILBRIDGE, 3502 Audubon Place, Houston, Texas. Dec., 1909.
DICKERSON, ROY E., Apartado 223, Maracaibo, Venezuela. Dec., 1918.
DODGE, RICHARD E., Storrs, Conn. August, 1897.
DOLMAGE, VICTOR, 510 Pacific Bldg., Vancouver, B. C. Dec., 1922.
DRAKE, NOAH FIELDS, Fayetteville, Ark. Dec., 1898.
DRESSER, JOHN A., 701 Eastern Townships Bank Bldg., Montreal, Canada. Dec., 1906.
DUNBAR, C. O., Yale University, New Haven, Conn. Dec., 1920.
EAKLE, ARTHUR S., University of California, Berkeley, Calif. Dec., 1899.
EATON, HARRY N., 101 Comstock Ave., Syracuse, N. Y. Dec., 1927.
ECKEL, EDWIN C., 1503 Decatur St., N. W., Washington, D. C. Dec., 1905.

EMERY, WILSON B., Casper, Wyoming. Dec., 1919.

*EMERSON, BENJAMIN K., Amherst, Mass.

EMMONS, WILLIAM H., Univ. of Minnesota, Minneapolis, Minn. Dec., 1912.

*FAIRCHILD, HERMAN L., University of Rochester, Rochester, N. Y.

FARRINGTON, OLIVER C., Field Museum of Natural History, Chicago, Ill. Dec., 1895.

FATH, A. E., Chrisman, Ill. Dec., 1920.

FENNEMAN, NEVIN M., University of Cincinnati, Cincinnati, Ohio. Dec., 1904.

FENNER, CLARENCE N., Geophysical Laboratory, Washington, D. C. Dec., 1911.

FERGUSON, H. G., U. S. Geological Survey, Washington, D. C. Dec., 1920.

FETTKE, CHARLES R., Carnegie Institute of Technology, Pittsburgh, Pa. Dec., 1924.

FIELD, RICHARD M., Princeton University, Princeton, N. J. Dec., 1926.

FINLAY, GEORGE I., New York University, New York, N. Y. Dec., 1928.

FISHER, CASSIUS ASA, 711 First Nat'l Bank Bldg., Denver, Colo. Dec., 1908.

FOERSTE, AUGUST F., 129 Wroe Ave., Dayton, Ohio. Dec., 1899.

FOHS, FERDINAND JULIUS, 51 East 42d St., New York, N. Y. Dec., 1923.

FORD, WILLIAM E., Sheffield Scientific School, New Haven, Conn. Dec., 1915.

FOYE, W. G., Wesleyan University, Middletown, Conn. Dec., 1919.

FULLER, MYRON L., 60 Main St., Brockton, Mass. Dec., 1898.

GALE, HOYT STODDARD, 1775 Hill Drive, Eagle Rock, Los Angeles, Calif. Dec., 1926.

GALLOWAY, J. J., Columbia University, New York, N. Y. Dec., 1920.

GALPIN, SIDNEY L., West Virginia University, Morgantown, W. Va. Dec., 1917.

GANE, HENRY STEWART, Rural Del. No. 1, Santa Barbara, Calif. Dec., 1896.

GARDNER, JAMES H., 626 Kennedy Bldg., Tulsa, Okla. Dec., 1911.

GARDNER, JULIA A., U. S. Geological Survey, Washington, D. C. Dec., 1920.

GEORGE, RUSSELL D., University of Colorado, Boulder, Colo. Dec., 1906.

GIDLEY, JAMES WILLIAM, U. S. Nat'l Museum, Washington, D. C. Dec., 1922.

GILBERT, PHILIP G. B., 30 Chestnut Park, Toronto, 5, Canada. Dec., 1928.

GILES, ALBERT W., University of Arkansas, Fayetteville, Ark. Dec., 1921.

GILL, ADAM CAPEN, Cornell University, Ithaca, N. Y. Dec., 1888.

GILLSON, JOSEPH LINCOLN, Northwestern University, Evanston, Ill. Dec., 1928.

GILLULY, JAMES, U. S. Geological Survey, Washington, D. C. Dec., 1927.

GILMORE, CHARLES WHITNEY, U. S. National Museum, Washington, D. C. Dec., 1924.

GLENN, L. C., 2111 Garland Ave., Nashville, Tenn. June, 1900.

GOLDMAN, MARCUS I., U. S. Geol. Survey, Washington, D. C. Dec., 1916.

GOLDRING, WINIFRED, New York State Museum, Albany, N. Y. Dec., 1921

GOLDTHWAIT, JAMES WALTER, Dartmouth College, Hanover, N. H. Dec., 1909.

GORDON, CHARLES H., University Library, University of Tennessee, Knoxville, Tenn. August, 1893.

GORDON, CLARENCE E., Massachusetts Agricultural College, Amherst, Mass. Dec., 1913.

GOULD, CHARLES N., 215 S. Webster St., Norman, Okla. Dec., 1904.

GRABAU, AMADEUS W., Government University, Peking, China. Dec. 1898.

GRANGER, WALTER, American Museum of Natural History, New York, N. Y. Dec., 1911.

GRANT, ULYSSES SHERMAN, Northwestern Univ., Evanston, Ill. Dec., 1890.
GRASTY, JOHN MARSHALL, Box 458, Charlottesville, Va. Dec., 1911.
GRATON, LOUIS C., Rotch Building, Cambridge, Mass. Dec., 1913.
GREGORY, HERBERT E., Yale University, New Haven, Conn. August, 1901.
GREENE, FRANK COOK, 1434 S. Cincinnati Ave., Tulsa, Okla. Dec., 1917.
GRIMSLEY, GEORGE P., 4405 Underwood Rd. (Guilford), Baltimore, Md. August, 1895.
GROUT, FRANK F., University of Minnesota, Minneapolis, Minn. Dec., 1918.
GRUNER, JOHN, W., University of Minnesota, Minneapolis, Minn. Dec., 1923.
GUNTER, HERMAN, State Geological Survey, Tallahassee, Fla. Dec., 1926.
*GURLEY, WILLIAM F. E. R., 6151 University Ave., Chicago, Ill. 1888-1900. Re-elected Dec., 1914.
HALBERSTADT, BAIRD, Pottsville, Pa. Dec., 1909.
HALL, GEORGE M., University of Tennessee, Knoxville, Tenn. Dec., 1926.
HANCE, J. H., State School of Mines, Corvallis, Ore. Dec., 1920.
HANCOCK, E. T., Teleajen Works Romano-Americana, Ploesti, Rumania. Dec., 1919.
HARDER, E. C., 1111 Harrison Bldg., Philadelphia, Pa. Dec., 1918.
HARES, C. J ., 305 Franklin St., Denver, Colo. Dec., 1920.
HARRIS, GILBERT D., Cornell University, Ithaca, N. Y. Dec., 1903.
HARTNAGEL, CHRIS A., New York State Museum, Albany, N. Y. Dec. 1913.
HASTINGS, JOHN B., 8663 Cypress Ave., Southgate, Calif. May, 1889.
*HAWORTH, ERASMUS, University of Kansas, Lawrence, Kans.
HAY, OLIVER P., Carnegie Institution, Washington, D. C. Dec., 1921.
HAYES, ALBERT O., Rutgers University, New Brunswick, N. J. Dec., 1919.
HAYNES, WINTHROP PERRIN, 82 Avenue des Champs Elysees, Paris, France. Dec., 1926.
HEALD, K. C. 1161 Frick Bldg. Annex, Pittsburgh, Pa. Dec., 1920.
HENDERSON, JUNIUS, University of Colorado, Boulder, Colo. Dec., 1925.
HENNEN, RAY V., Transcontinental Oil Co., Tulsa., Okla. Dec. 1914.
HERSHEY OSCAR H., Crocker Bldg., San Francisco, Calif. Dec. 1909.
HESS, FRANK L., U. S. Bureau of Mines, Washington, D. C. Dec., 1921.
HEWETT, DONNEL F., U. S. Geological Survey, Washington, D. C. Dec., 1916.
HIGGINS, DANIEL F., 747 N. Jefferson Ave., Loveland, Colo. Dec., 1925.
HILL, J. M., 2671 Shasta Road, Berkeley, Calif. Dec., 1920.
*HILL, ROBERT T., Hotel Commodore, Los Angeles, Calif.
HILLS, THOMAS MCDOUGALL, Vassar College, Poughkeepsie, N. Y. Dec., 1924.
HINDS, HENRY, 1153 Laurel Ave., St. Paul, Minn. Dec., 1912.
HINTZE, FERDINAND FRIIS, 580 Corona St., Denver, Colo. Dec., 1917.
HOBBS, WILLIAM H., University of Michigan, Ann Arbor, Mich. August, 1891.
HODGE, EDWIN T., University of Oregon, Eugene, Ore. Dec. 1927.
HOLDEN, ROY J., Virginia Polytechnic Institute, Blacksburg, Va. Dec., 1914.
HOLLAND, WILLIAM JACOB, Carnegie Museum, Pittsburgh, Pa. Dec., 1910.
HOLLICK, ARTHUR, N. Y. Botanical Garden, New York, N. Y. August, 1898.
HONESS, CHARLES W., Gypsy Oil Co., Tulsa, Okla. Dec. 1927.
HOOTS, HAROLD W., U. S. Geological Survey, California Institute of Technology, Pasadena, Calif. Dec., 1928.
HOPKINS, O. B., Internat. Petr. Co., Ltd., 56 Church St., Toronto, Canada. Dec., 1919.

HOPKINS, THOMAS C., Syracuse University, Syracuse, N. Y. Dec., 1894.
HOTCHKISS, WILLIAM OTIS, College of Mines, Houghton, Mich. Dec., 1911.
HOWE, ERNEST, Litchfield, Conn. Dec., 1903.
HOWELL, BENJAMIN F., Princeton University, Princeton, N. J. Dec., 1926.
HUBBARD, GEORGE D., Oberlin College, Oberlin, Ohio. Dec., 1914.
HUDSON, GEORGE H., 39 Broad Street, Plattsburg, N. Y. Dec., 1917.
HUME, GEORGE S., Geological Survey of Canada, Ottawa, Canada. Dec., 1923.
HUNT, WALTER F., University of Michigan, Ann Arbor, Mich. Dec., 1914.
HUNTINGTON, ELLSWORTH, Yale University, New Haven, Conn. Dec., 1906.
HUSSAKOF, LOUIS, 1537 50th St., Brooklyn, N. Y. Dec., 1910.
HYDE, J. E., Western Reserve University, Cleveland, Ohio. Dec., 1916.
JACKSON, ROBERT T., Peterborough, N. H. August, 1894.
JACOBS, ELBRIDGE C., University of Vermont, Burlington, Vt. Dec., 1921.
JEFFERSON, MARK S. W., Michigan State Normal College, Ypsilanti, Mich. Dec., 1904.
JEFFREY, EDWARD C., Harvard University, Cambridge, Mass. Dec., 1914.
JENKINS, OLAF P., % Dr. Oliver P. Jenkins, Stanford University, Calif. Dec., 1921.
JOHANNSEN, ALBERT, University of Chicago, Chicago, Ill. Dec., 1908.
JOHNSON, B. L., U. S. Bureau of Mines, Washington, D. C. Dec., 1919.
JOHNSON, DOUGLAS WILSON, Columbia University, New York, N. Y. Dec., 1906.
JOHNSON, ROSWELL H., University of Pittsburgh, Pittsburgh, Pa. Dec., 1918.
JONAS, ANNA I., Room 4230, U. S. Geological Survey, Washington, D. C. Dec., 1922.
JONES, J CLAUDE, University of Nevada, Reno, Nev. Dec., 1927.
KATZ, FRANK JAMES, Bureau of Mines, Washington, D. C. Dec., 1912.
KAY, GEORGE FREDERICK, State Univ. of Iowa, Iowa City, Iowa. Dec., 1908.
KEITH, ARTHUR, U. S. Geological Survey, Washington, D. C. May, 1889.
KERR, PAUL F., Columbia University, New York, N. Y. Dec., 1927.
KEW, W. S. W., 1215 N. Howard St., Glendale, Calif. Dec., 1920.
KEYES, CHARLES ROLLIN, 944 Fifth St., Des Moines, Iowa. August, 1890.
KINDLE, EDWARD M., Victoria Memorial Museum, Ottawa, Canada. Dec., 1905.
KIRK, CHARLES T., 1226 S. Newport St., Tulsa, Okla. Dec., 1915.
KIRK, EDWIN, U. S. Geological Survey, Washington, D. C. Dec., 1912.
KIRKHAM, V. R. D., University of Chicago, Chicago, Ill. Dec., 1927.
KNAPPEN, RUSSELL S., P. O. Box 2044, Tulsa, Okla. Dec., 1926.
KNIGHT, CYRIL WORKMAN, Nipissing Mining Co., Ltd., Cobalt, Ontario, Canada. Dec., 1911.
KNOPF, ADOLPH, Yale Station, New Haven, Conn. Dec., 1911.
KNOPF, ELEANORA BLISS, 105 East Rock Road, New Haven, Conn. Dec., 1919.
KRAUS, EDWARD HENRY, Univ. of Michigan, Ann Arbor, Mich. June, 1902.
KUMMEL, HENRY B., Trenton, N. J. Dec., 1895.
*KUNZ, GEORGE F., 401 Fifth Ave., New York, N. Y.
LAHEE, FREDERIC H., American Exchange Natl. Bank Bldg., Dallas, Texas. Dec., 1917.
LANDES, HENRY, University of Washington, University Station, Seattle, Wash. Dec., 1908.
LANE, ALFRED C., Tufts College, Mass. Dec., 1889.

LARSEN, ESPER S., JR., Geol. Mus., Harvard Univ., Cambridge, Mass. Dec., 1914.

LAWSON, ANDREW C., University of California, Berkeley, Calif. May, 1889.

LEES, JAMES H., Iowa Geological Survey, Des Moines, Iowa. Dec., 1914.

LEIGHTON, MORRIS M., Illinois Geological Survey, Urbana, Ill. Dec., 1921.

LEITH, CHARLES K., University of Wisconsin, Madison, Wis. Dec., 1902.

LEONARD ARTHUR G., State University of North Dakota, Grand Forks, N. Dak. Dec., 1901.

LEVERETT, FRANK, Ann Arbor, Mich. August, 1890.

LEWIS, JOSEPH VOLNEY, % Gulf Companies, 21 State St., New York, N. Y. Dec., 1906.

LIDDLE, RALPH ALEXANDER, The Pure Oil Co., P. O. Box 1007, Fort Worth, Texas. Dec., 1921.

LINDGREN, WALDEMAR, Massachusetts Institute of Technology, Cambridge, Mass. August, 1890.

LISBOA, MIGUEL A. R., Caixa postal 829, Ave. Rio Branco 46-V, Rio de Janeiro, Brazil. Dec., 1913.

LITTLE, HOMER P., Clark University, Worcester, Mass. Dec., 1918.

LLOYD, E. R., P. O. Box 652, Roswell, N. Mex. Dec., 1919.

LOBECK, ARMIN KOHL, University of Wisconsin, Madison, Wis. Dec., 1924.

LOCKE, AUGUSTUS, 788 Mills Bldg., San Francisco, Calif. Dec., 1927.

LOGAN, WILLIAM N., Indiana University, Bloomington, Ind. Dec., 1917.

LONGWELL, CHESTER R., Yale University, New Haven, Conn. Dec., 1923.

LONSDALE, JOHN T., Agricultural and Mechanical College, College Station, Texas. Dec., 1928.

LOOMIS, FREDERICK BREWSTER, Amherst College, Amherst, Mass. Dec., 1909.

LOUDERBACK, GEORGE D., University of California, Berkeley, Calif. June, 1902.

LOUGHLIN, GERALD F., U. S. Geological Survey, Washington, D. C. Dec., 1916.

LOVERING, THOMAS S., U. S. Geological Survey, Washington, D. C. Dec., 1927.

LOW, ALBERT P., 154 McLaren St., Ottawa, Canada. Dec., 1905.

LULL, RICHARD SWANN, Yale University, New Haven, Conn. Dec., 1909.

LUPTON, CHARLES T., 611 17th St., Denver, Colo. Dec., 1916.

MCCALLIE, SAMUEL WASHINGTON, Atlanta, Ga. Dec., 1909.

MCCASKEY, HIRAM D., Central Point, Oregon. Dec., 1904.

MCCONNELL, RICHARD G., Rideau Club, Ottawa, Canada. May, 1889.

MCCOY, ALEX. W., 919 East Grand Ave., Ponca City, Okla. Dec., 1922.

MACDONALD, DONALD F., 16 Eastover Court, Louisville, Ky. Dec., 1915.

MACFARLANE, JAMES RIEMAN, Woodland Road, Pittsburgh, Pa. August, 1891.

MACKAY, BERTRAM R., Geological Survey, Ottawa, Canada. Dec., 1922.

MCKELLAR, PETER, Fort William, Ontario, Canada. August, 1890.

MCLAUGHLIN, DONALD H., Rotch Bldg., Harvard University, Cambridge, Mass. Dec., 1922.

MCLEAN, FRANK HARRIS, Geological Survey, Ottawa, Canada. Dec., 1923.

MALOTT, CLYDE A., Indiana University, Bloomington, Ind. Dec., 1926.

MANSFIELD, GEORGE R., 2067 Park Rd. N. W., Washington, D. C. Dec., 1909.

MARBUT, CURTIS F., Bureau of Soils, Washington, D. C. August, 1897.

MARSTERS, VERNON F., 3501 Smart Ave., Kansas City, Mo. Aug., 1892.

MARTIN, GEORGE C., 3126 38th Street, Washington, D. C. June, 1902.

MARTIN, LAWRENCE, Library of Congress, Washington, D. C. Dec., 1909.
MATHER, KIRTLEY F., Harvard Geological Museum, Cambridge, Mass. Dec., 1918.
MATHEWS, EDWARD B., Johns Hopkins University, Baltimore, Md. Aug., 1895.
MATSON, GEORGE C., 1534 East 17th Place, Tulsa, Okla. Dec., 1918.
MATTHES, FRANÇOIS E., U. S. Geol. Survey, Washington, D. C. Dec., 1914.
MATTHEW, W. D., University of California, Berkeley, Calif. Dec., 1903.
MAURY, CARLOTTA J., 50-A Locust Hill Ave., Yonkers, N. Y. Dec., 1920.
MAYNARD, THOMAS POOLE, 759 Myrtle St., N. E., Atlanta, Ga. Dec., 1914.
MEAD, WARREN JUDSON, University of Wisconsin, Madison, Wis. Dec., 1916.
MEHL, MAURICE G., University of Missouri, Columbia, Mo. Dec., 1922.
MEINZER, OSCAR E., U. S. Geological Survey, Washington, D. C. Dec., 1916.
MENDENHALL, WALTER C., U. S. Geol. Survey, Washington, D. C. June, 1902.
MERRIAM, JOHN C., Carnegie Institution, Washington, D. C. August, 1895.
MERRILL, GEORGE P., U. S. National Museum, Washington, D. C. Dec., 1888.
MERTIE, JOHN BEAVER, JR., 112 Park Ave., Takoma Park, D. C. Dec., 1923.
MERWIN, HERBERT E., Geophysical Laboratory, Washington, D. C. Dec., 1914.
MILLER, ARTHUR M., Bellevue Cottage, Sunset Drive, Asheville, N. C. Dec. 1897.
MILLER, BENJAMIN L., Lehigh University, Bethlehem, Pa. Dec., 1904.
MILLER, WILLIAM JOHN, University of California at Los Angeles, Los Angeles, Calif. Dec., 1909.
MISER, HUGH D., U. S. Geological Survey, Washington, D. C. Dec., 1916.
MOFFIT, FRED HOWARD, U. S. Geological Survey, Washington, D. C. Dec., 1912.
MONNETT, VICTOR E., University of Oklahoma, Norman, Okla. Dec., 1926.
MOORE, ELWOOD S., University of Toronto, Toronto, Canada. Dec., 1911.
MOORE, RAYMOND C., University of Kansas, Lawrence, Kans. Dec., 1921.
MOOK, CHARLES C., Metuchen, N. J. Dec., 1922.
MORGAN, GEORGE D., Dixie Oil Co., Shreveport, La. Dec., 1927.
MORRIS, F. K., Massachusetts Institute of Technology, Cambridge, Mass. Dec., 1927.
MORSE, WILLIAM C., Agricultural and Mechanical College, Miss. Dec., 1925.
NELSON, W. A., University, Va. Dec., 1920.
NEWLAND, DAVID HALE, 94 Menand Road, Albany, N. Y. Dec., 1906.
NOBLE, LEVI F., Valyermo, Calif. Dec., 1916.
NOÉ, ADOLF C., University of Chicago, Chicago, Ill. Dec., 1927.
NORTON, WILLIAM H., Cornell College, Mount Vernon, Iowa. Dec., 1895.
O'CONNELL, MARJORIE, (Shearon), 137-70 Westgate Ave., Springfield Gardens, L. I. Dec., 1919.
OGILVIE, IDA HELEN, Barnard College, Columbia University, New York, N. Y. Dec., 1906.
O'HARRA, CLEOPHAS C., South Dakota School of Mines, Rapid City, S. Dak. Dec., 1904.
OHERN, DANIEL WEBSTER, 515 W. 14th St., Oklahoma City, Okla. Dec., 1911.
O'NEILL, J. J., McGill University, Montreal, Canada. Dec., 1920.
OSBORN, HENRY F., American Museum of Natural History, New York, N. Y. August, 1894.

OVERBECK, ROBERT M., % Caracoles Tin Co. of Bolivia, Casilla No. 674. La Paz, Bolivia, South America. Dec., 1921.

PACK, FREDERICK J., University of Utah, Salt Lake City, Utah. Dec., 1926.

PACK, ROBERT W., Box 790, Beaumont, Texas. Dec., 1916.

PAIGE, SIDNEY, Venezolana Petroleo, Apartado 73, Caracas, Venezuela. Dec., 1911.

PALACHE, CHARLES, Harvard University, Cambridge, Mass. August, 1897.

PALMER, HAROLD S., University of Hawaii, Honolulu, Hawaii. Dec., 1927.

PARKS, WILLIAM A., University of Toronto, Toronto, Canada. Dec., 1906.

PARSONS, ARTHUR LEONARD, University of Toronto, Toronto, Canada. Dec., 1928.

*PATTON, HORACE B., Atascadero, Calif.

PENROSE, RICHARD A. F., JR., Bullitt Bldg., Philadelphia, Pa. May, 1889.

PERKINS, GEORGE H., University of Vermont, Burlington, Vt. June, 1902.

PERRY, JOSEPH H., 276 Highland St., Worcester, Mass. Dec., 1888.

PHALEN, WILLIAM C., Drawers 1 and 2, Syracuse, N. Y. Dec., 1912.

PHILLIPS, ALEXANDER H., Princeton University, Princeton, N. J. Dec., 1914.

PIPER, ARTHUR M., U. S. Geological Survey, Washington, D. C. Dec., 1928.

PLUMMER, FREDERICK B., Bureau of Economic Geology, Austin, Texas. Dec., 1925.

POGUE, JOSEPH E., 42 West 12th St., New York City. Dec., 1911.

POWERS, SIDNEY, Amerada Petr. Corp., Tulsa, Okla. Dec., 1920.

PRATT, JOSEPH H., North Carolina Geol. Survey, Chapel Hill, N. C. Dec., 1898.

PRATT, W. E., Humble Oil and Refining Co., Houston, Texas. Dec., 1920.

PRICE, W. ARMSTRONG, 1312 Niels Esperson Bldg., Houston, Texas. Dec., 1916.

PRINDLE, LOUIS M., U. S. Geological Survey, Washington, D. C. Dec., 1912.

PROUTY, WILLIAM F., Univ. of North Carolina, Chapel Hill, N. C. Dec., 1911.

QUIRKE, TERENCE T., University of Illinois, Urbana, Ill. Dec., 1921.

RANSOME, FREDERICK L., California Institute of Technology, Pasadena, Calif. August, 1895.

RAYMOND, PERCY EDWARD, Museum of Comparative Zoology, Cambridge, Mass. Dec., 1907.

REBER, LOUIS E., Box 1096, Jerome, Ariz. Dec., 1923.

REED, RALPH D., 1717 S. Third St., Alhambra, Calif. Dec., 1927.

REEDS, CHESTER A., American Museum of Natural History, New York, N. Y. Dec., 1913.

REESIDE, JOHN B., JR., U. S. Geological Survey, Hyattsville, Md. Dec., 1921.

REEVES, FRANK, U. S. Geological Survey, Washington, D. C. Dec., 1924.

REGER, DAVID B., Box 816, Morgantown, W. Va. Dec., 1918.

REID, HARRY FIELDING, Johns Hopkins University, Baltimore, Md. Dec., 1892.

REINECKE, LEOPOLD, P. O. Box 2682, Johannesburg, Transvaal, South Africa. Dec., 1916.

RENICK, B. COLEMAN, Shell Petroleum Corporation, Box 1865, Houston, Texas. Dec., 1926

RESSER, CHARLES E., U. S. National Museum, Washington, D. C. Dec., 1926.

RICH, JOHN LYON, Box 3, Ottawa, Kans. Dec., 1912.

RICHARDS, R. W., % Standard Oil Co. of Venezuela, Apartado 85, Maracaibo, Venezuela. Dec., 1920.

RICHARDSON, CHARLES H., Syracuse University, Syracuse, N. Y. Dec., 1899.
RICHARDSON, GEORGE B., U. S. Geol. Survey, Washington, D. C. Dec., 1908.
RICHARZ, STEPHEN, St. Mary's College, Techny, Ill. Dec., 1926.
RIES, HEINRICH, Cornell University, Ithaca, N. Y. Dec., 1893.
RIGGS, ELMER S., Field Museum of Natural History, Chicago, Ill. Dec., 1911.
ROBERTS, JOSEPH K., University of Virginia, Charlottesville, Va. Dec., 1926.
RODDY, H. JUSTIN, 645 W. Chestnut St., Lancaster, Pa. Dec., 1919.
ROGERS, AUSTIN F., Stanford University, Calif. Dec., 1918.
ROSE, BRUCE, Queens University, Kingston, Ontario, Canada. Dec., 1916.
ROSS, CLARENCE, U. S. Geological Survey, Washington, D. C. Dec., 1926.
RUBEY, WILLIAM W., U. S. Geological Survey, Washington, D. C. Dec., 1927.
RUEDEMANN, RUDOLF, New York State Museum, Albany, N. Y. Dec., 1905.
RUTLEDGE, JOHN JOSEPH, State Bureau of Mines, 22 Light St., Baltimore, Md. Dec., 1911.
SALES, RENO H., Anaconda Copper Mining Co., Butte, Mont. Dec., 1916.
SAMPSON, EDWARD, Princeton University, Princeton, N. J. Dec., 1924.
SARDESON, FREDERICK W., 414 Harvard St., S. E. Minneapolis, Minn. Dec., 1892.
SAVAGE, THOMAS EDMUND, University of Illinois, Urbana, Ill. Dec., 1907.
SAYLES, ROBERT WILCOX, Harvard University, Chestnut Hill, Mass. Dec., 1917.
SCHALLER, WALDEMAR T., U. S. Geol. Survey, Washington, D. C. Dec., 1918.
SCHENCK, HUBERT G., Stanford University, Calif. Dec., 1927.
SCHNEIDER, HYRUM, University of Utah, Salt Lake City, Utah. Dec., 1927.
SCHOEWE, WALTER H., University of Kansas, Lawrence, Kans. Dec., 1927.
SCHOFIELD, S. J., University of British Columbia, Vancouver, B. C. Dec., 1918.
SCHRADER, FRANK C., U. S. Geological Survey, Washington, D. C. Aug., 1901.
SCHUCHERT, CHARLES, Yale University, New Haven, Conn. August, 1895.
SCHULTZ, ALFRED R., 800 Vine Street, Hudson, Wis. Dec., 1912.
SCHWARTZ, GEORGE M., Univ. of Minnesota, Minneapolis, Minn. Dec., 1923.
SCOTT, IRVING D., University of Michigan, Ann Arbor, Mich. Dec., 1923.
SCOTT, WILLIAM B., Princeton University, Princeton, N. J. August, 1892.
SEAMAN, ARTHUR E., Michigan College of Mines, Houghton, Mich. Dec., 1904.
SEARS, JULIAN DUCKER, 209 E. Underwood St., Chevy Chase, Md. Dec., 1924.
SELLARDS, ELIAS H., University of Texas, Austin, Texas. Dec., 1905.
SEMMES, DOUGLAS R., Cinco de Mayo 32, Mexico D. F., Mexico. Dec., 1921.
SHALER, MILLARD K., 66 Rue Des Colonies, Brussels, Belgium. Dec., 1914.
SHATTUCK, GEORGE BURBANK, Mt. Royal Station, Baltimore, Md. Aug., 1899.
SHAW, EUGENE W., Room 1560, 81 New Street, New York, N. Y. Dec., 1912.
SHEDD, SOLON, Box 1888, Stanford University, Calif. Dec., 1904.
SHEPARD, EDWARD M., 1403 Benton Ave., Springfield, Mo. August, 1901.
SHEPARD, FRANCIS P., University of Illinois, Urbana, Ill. Dec., 1927.
SHIMEK, BOHUMIL, University of Iowa, Iowa City, Iowa. Dec., 1904.
SHIMER, HERVEY WOODBURN, Massachusetts Institute of Technology, Cambridge, Mass. Dec., 1910.
SHULER, E. W., South Methodist University, Dallas, Texas. Dec., 1920.
SIEBENTHAL, CLAUDE E., U. S. Geol. Survey, Washington, D. C. Dec., 1912.
*SIMONDS, FREDERICK W., University of Texas, Austin, Texas.

SIMPSON, HOWARD E., University of North Dakota, Grand Forks, N. Dak. Dec., 1923.

SINCLAIR, WILLIAM JOHN, Princeton University, Princeton, N. J. Dec., 1906.

SINGEWALD, JOSEPH T., JR., Johns Hopkins University, Baltimore, Md. Dec., 1911.

SMITH, BURNETT, West Lake St., Skaneateles, N. Y. Dec., 1911.

SMITH, EDWARD S. C., Union College, Schenectady, N. Y., Dec., 1928.

SMITH, GEORGE OTIS, U. S. Geological Survey, Washington, D. C. Aug., 1897.

SMITH, PHILIP S., U. S. Geological Survey, Washington, D. C. Dec., 1909.

SMITH, RICHARD A., Biological Survey of Michigan, Lansing, Mich. Dec., 1921.

SMITH, STANLEY, University of Bristol, Bristol, England. Dec., 1922.

SMITH, WARREN DU PRÉ, University of Oregon, Eugene, Ore. Dec., 1909.

SMITH, W. S. TANGIER, 640 Tennyson Ave., Palo Alto, Calif. June, 1902.

SMYTH, CHARLES H., JR., Princeton University, Princeton, N. J. Aug., 1892.

SMYTH, HENRY L., Harvard University, Cambridge, Mass. August, 1894.

SNIDER, LUTHER C., 110 Crescent Ave., Leonia, N. J. Dec., 1927.

SOMERS, R. E., Oil and Gas Bldg., University of Pittsburgh, Pittsburgh, Pa. Dec., 1919.

SOPER, EDGAR K., 845 Muirfield Road, Los Angeles, Calif. Dec., 1918.

SOSMAN, R. B., Federal Shipbuilding & Dry Dock Co., Kearny, N. J. Dec., 1920.

SPEIGHT, ROBERT, Canterbury College, Christ Church, New Zealand. Dec., 1916.

SPENCER, ARTHUR COE, U. S. Geological Survey, Washington, D. C. Dec., 1896.

SPIEKER, EDMUND MAUTE, State University of Ohio, Columbus, Ohio. Dec., 1924.

SPURR, JOSIAH E., % Engineering and Mining Journal, 10th Ave. and 36th St., New York, N. Y. Dec., 1894.

STANLEY-BROWN, JOSEPH, 151 Quentin St., Kew Gardens, L. I., N. Y. August, 1892.

STANTON, TIMOTHY W., U. S. Nat'l Museum, Washington, D. C. August, 1891.

STAUFFER, CLINTON R., Univ. of Minnesota, Minneapolis, Minn. Dec., 1911.

STEARNS, HAROLD T., U. S. Geological Survey, Washington, D. C. Dec., 1927.

STEBINGER, EUGENE, JR., 719 Edificio Banco Boston, Buenos Aires, Argentina. Dec., 1916.

STEIDTMANN, EDWARD, Virginia Military Institute, Lexington, Va. Dec., 1916.

STEPHENSON, LLOYD W., U. S. Geol. Survey, Washington, D. C. Dec., 1911.

STOCK, CHESTER, California Institute of Technology, Pasadena, Calif. Dec., 1927.

STOLLER, JAMES HOUGH, Galway, Saratoga County, N. Y. Dec., 1917.

STONE, RALPH WALTER, State Geological Survey, Harrisburg, Pa. Dec., 1912.

STOSE, GEORGE WILLIS, U. S. Geological Survey, Washington, D. C. Dec., 1908.

STOUT, WILBER, Geological Survey of Ohio, Columbus, Ohio. Dec., 1918.

SUSSMILCH, CARL ADOLPH, East Sydney Technical College, Darlinghurst, Sydney, Australia. Dec., 1925.

SWARTZ, CHARLES K., Johns Hopkins University, Baltimore, Md. Dec., 1908.

SWARTZ, JOEL H., University of North Carolina, Chapel Hill, N. C. Dec., 1927.

SWINNERTON, ALLYN C., Antioch College, Yellow Springs, Ohio. Dec., 1928.
TABER, STEPHEN, University of South Carolina, Columbia, S. C. Dec., 1914.
TAFF, JOSEPH A., 629 Cooper St., Palo Alto, Calif. August, 1895.
TALBOT, MIGNON, Mount Holyoke College, South Hadley, Mass. Dec., 1913.
TALMADGE, JAMES E., 47 E. South Temple St., Salt Lake City, Utah. Dec., 1897.
TANTON, THOMAS L., Geological Survey, Ottawa, Canada. Dec., 1927.
TARR, WILLIAM ARTHUR, 704 Westwood Ave., Columbia, Mo. Dec., 1917.
TAYLOR, FRANK B., 420 Downing Ave., Fort Wayne, Ind. Dec., 1895.
THIEL, GEORGE A., University of Minnesota, Minneapolis, Minn. Dec., 1925.
THOM, WILLIAM TAYLOR, JR., Princeton University, Princeton, N. J. Dec., 1924.
THOMAS, ABRAM O., University of Iowa, Iowa City, Iowa. Dec., 1921.
THOMPSON, DAVID G., U. S. Geological Survey, Washington, D. C. Dec., 1928.
THORPE, MALCOLM R., 1463 Yale Station, New Haven, Conn. Dec., 1923.
THWAITES, FREDRIK T., Science Hall, Madison, Wis. Dec., 1925.
TILTON, J. L., Morgantown, W. Va. Dec., 1920.
TOLMACHOFF, I. P., Carnegie Museum, Pittsburgh, Pa. Dec., 1927.
TOMLINSON, CHARLES WELDON, 1610 Bixby Ave., Ardmore, Okla. Dec., 1917.
TRASK, PARKER D., Box 2261, Stanford University, Calif. Dec., 1927.
TROWBRIDGE, ARTHUR C., State Univ. of Iowa, Iowa City, Iowa. Dec., 1913.
TROXELL, EDWARD L., Trinity College, Hartford, Conn. Dec., 1923.
*TURNER, HENRY W., Mills Bldg., San Francisco, Calif.
TWENHOFEL, WILLIAM H., University of Wisconsin, Madison, Wis. Dec., 1913.
TYRRELL, JOSEPH B., 810 Lumsden Bldg., Toronto 2, Canada. May, 1889.
UDDEN, JOHAN A., University of Texas, Austin, Texas. August, 1897.
*ULRICH, EDWARD O., U. S. Geological Survey, Washington, D. C. 1888-1897. Re-elected Dec., 1903.
UMPLEBY, JOSEPH B., University of Oklahoma, Norman, Okla. Dec., 1913.
*UPHAM, WARREN, Minnesota Historical Society, St. Paul, Minn.
VAN DER GRACHT, WILLIAM A. J. M. VAN WATERSCHOOT, Schloss Hainfeld, Feldbach Austria. Dec., 1928.
VAN HORN, F. R., Case School of Applied Science, Cleveland, Ohio. Dec., 1898.
VAN TUYL, FRANCIS M., Colorado School of Mines, Golden, Colo. Dec., 1917.
VAUGHAN, T. WAYLAND, Scripps Institution, La Jolla, Calif. August, 1896.
VEATCH, ARTHUR CLIFFORD, 7 Central Drive, Port Washington, N. Y. Dec., 1906.
VISHER, STEPHEN S., 817 E. Second St., Bloomington, Ind. Dec., 1923.
VON ENGELN, OSCAR D., Cornell University, Ithaca, N. Y. Dec., 1927.
WADE, BRUCE, State Geological Survey, Nashville, Tenn. Dec., 1920.
WALKER, THOMAS L., University of Toronto, Toronto, Canada. Dec., 1903.
WANDKE, ALFRED, Consolidated Mining & Milling Co., Guanajuato, Mexico. Dec., 1928.
WARD, FREEMAN, 40 McCartney St., Easton, Pa. Dec., 1925.
WARD, LEONARD KEITH, Department of Mines, Adelaide, South Australia. Dec., 1924.
WARING, GERALD A., Margay Oil Corp., Box 2103, Tulsa, Okla. Dec., 1921.
WARREN, CHARLES H., Yale University, New Haven, Conn. Dec., 1901.

WASHBURNE, C. W., 27 William St., New York, N. Y. Dec., 1919.
WASHINGTON, HENRY S., Geophysical Laboratory, Washington, D. C. Aug., 1896.
WEAVER, CHARLES E., University of Washington, Seattle, Wash. Dec., 1913.
WEED, WALTER H., Post Road, Scarsdale, N. Y. May, 1889.
WEGEMANN, CARROLL H., Pan American Exploration Co., 122 E. 42nd St., New York, N. Y. Dec., 1912.
WEIDMAN, SAMUEL, 814 Monett St., Norman, Okla. Dec., 1903.
WELLS, ROGER C., U. S. Geological Survey, Washington, D. C. Dec., 1921.
WENTWORTH, CHESTER K., Washington University, St. Louis, Mo. Dec., 1923.
WESTGATE, LEWIS G., 124 Oak Hill Ave., Delaware, Ohio. August, 1894.
WHERRY, EDGAR T., Bureau of Chemistry, Washington, D. C. Dec., 1915.
WHITE, DAVID, U. S. National Museum, Washington, D. C. May, 1889.
WHITE, LUTHER HERMAN, J. A. Hull Oil Co., Tulsa, Okla. Dec., 1928.
WHITLOCK, H. P., Amer. Museum of Natural History, N. Y. City. Dec., 1920.
WHITMAN, ALFRED RUSSELL, University of California at Los Angeles, Calif. Dec., 1928.
WHITNEY, FRANCIS L., University of Texas, Austin, Texas. Dec., 1923.
WIELAND, GEORGE REBER, Yale University, New Haven, Conn. Dec., 1910.
WILDER, FRANK A., North Holston, Smyth County, Va. Dec., 1905.
*WILLIAMS, EDWARD H., JR., Woodstock, Vt.
WILLIAMS, IRA A., 821 Spalding Bldg., Portland, Ore. Dec., 1905.
WILLIAMS, MERTON YARWOOD, Univ. of British Columbia, Vancouver, B. C. Dec., 1916.
WILLIS, BAILEY, Leland Stanford Jr. University, Stanford University, Calif. Dec., 1889.
WILSON, ALFRED W. G., Department of Mines, Ottawa, Canada. June, 1902.
WILSON, MORLEY EVANS, Geological Survey, Ottawa, Canada. Dec., 1916.
WINCHELL, ALEXANDER N., University of Wisconsin, Madison, Wis. Aug., 1901.
*WINSLOW, ARTHUR, 131 State St., Boston, Mass.
WOLFF, JOHN E., 360 S. Grand Ave., Pasadena, Calif. Dec., 1889.
WOOD, HARRY OSCAR, 200 N. San Rafael Ave., Pasadena, Calif. Dec., 1922.
WOODFORD, ALFRED O., Pomona College, Claremont, Calif. Dec., 1927.
WOODMAN, JOSEPH E., New York University, New York, N. Y. Dec., 1905.
WOODRING, WENDELL P., California Institute of Technology, Pasadena, Calif. Dec., 1921.
WOODRUFF, E. G., 1611 S. Detroit St., Tulsa, Okla. Dec., 1922.
WOOLNOUGH, WALTER GEORGE, Home and Territories Dept., Canberra, F. C. T., Australia. Dec., 1924.
WRATHER, WILLIAM E., 4300 Overhill Drive, Dallas Texas. Dec., 1923.
WRIGHT, CHARLES WILL, 2128 Wyoming Ave., Washington, D. C. Dec., 1909.
WRIGHT, FREDERIC E., Geophysical Laboratory, Washington, D. C. Dec., 1903.

CORRESPONDENTS DECEASED

CAPELLINI, GIOVANNI. Died 1924.
CREDNER, HERMAN. Died July 22, 1913.
DE STEFANI, CARLO. Died Dec. 12, 1924.
GEIKIE, SIR ARCHIBALD. Died Nov., 1924.
MICHEL-LÉVY, A. Died September, 1911.
KAYSER, EMANUEL. Died Nov. 29, 1927.
KILAN, W. Died 1926.
ROSENBUISCH, H. Died January 20, 1914.
SUESS, EDWARD. Died April 20, 1914.
TEALL, SIR J. J. H. Died July 2, 1924.
TSCHERNYSCHEW, TH. Died Jan. 15, 1914.
ZIRKEL, FERDINAND. Died June 11, 1912.

FELLOWS DECEASED

*Indicates Original Fellow (see article III of Constitution)

*Ashburner, Chas. A. Died Dec. 24, 1889.
Barlow, Alfred E. Died May 28, 1914.
Barrell, Joseph. Died May 4, 1919.
Beecher, Charles E. Died Feb. 14, 1904.
*Becker, George F. Died April 20, 1919.
Bell, Robert. Died June 18, 1917.
Bickmore, Albert S. Died Aug. 12, 1914.
Blake, Wm. Phipps. Died May 21, 1910.
Bowman, Amos. Died June 18, 1894.
Bownocker, J. Adams. Died Oct. 20, 1928.
*Branner, John C. Died March 1, 1922.
Brooks, Alfred H. Died Nov. 22, 1924.
Brown, Amos P. Died Oct. 9, 1917.
Buckley, Ernest R. Died Jan. 19, 1912.
Cairnes, D. D. Died June 14, 1917.
*Calvin, Samuel. Died April 17, 1911.
Carpenter, Frank R. Died April 1, 1910.
Castello, Antonio Del. Died Oct.28,1895.
*Chamberlin, T. C. Died Nov. 14, 1928.
Chapin, J. H. Died March 14, 1892.
Clark, William B. Died July 27, 1917.
Clarke, John Mason. Died May 29, 1925.
*Claypole, Edward W. Died Aug. 17, 1901.
*Comstock, Theo. B. Died July 26, 1915.
Cook, George H. Died Sept. 22, 1889.
*Cope, Edward D. Died April 12, 1897.
Cox, George H. Died August 20, 1922.
*Crosby, William O. Died Dec. 31, 1925.
*Cushing, H. P. Died April 14, 1921.
*Dana, James D. Died April 14, 1895.
Davis, Charles A. Died April 9, 1916.
Dawson, George M. Died March 2, 1901.
Dawson, Sir J. Wm. Died Nov. 19, 1899.
Day, David T. Died April 15, 1925.
Dean, Bashford. Died Dec. 7, 1928.
Derby, Orville A. Died Nov. 27, 1915.
*Diller, Joseph S. Died Nov. 13, 1928.
d'Invilliers, Edw. V. Died Jan. 4, 1928.
Drysdale, Chas. W. Died July 10, 1917.
*Dumble, Edwin T. Died Jan. 26, 1927.
Dutton, Clarence E. Died Jan. 4, 1912.
*Dwight, Wm. B. Died Aug. 29, 1906.
Eastman, Chas. R. Died Sept. 27, 1918.
*Eldridge, George H. Died June 29, 1905.
*Emmons, Samuel F. Died March 28, 1911.
Fontaine, Wm. M. Died April 30, 1913.
*Foote, Albert E. Died October 10, 1895.
*Frazer, Persifor. Died April 7, 1909.
*Fuller, Homer T. Died Aug. 14, 1908.
*Gilbert, Grove K. Died May 1, 1918.
Giroux, N. J. Died Nov. 30, 1891.
Hague, Arnold. Died May 14, 1917.
*Hall, Christopher W. Died May 10,1911.
*Hall, James. Died August 7, 1898.
Harrison, Sir J. B. Died Feb. 8, 1926.
Hatcher, John B. Died July 3, 1904.
*Hay, Robert. Died December 14, 1895.
Hayes, C. Willard. Died Feb. 9, 1916.
*Heilprin, Angelo. Died July 17, 1907.
Hice, Richard R. Died March 27, 1925.
Hilgard, Eugene W. Died Jan. 8, 1916.
Hill, Frank A. Died July 13, 1915.
Hills, Richard C. Died Aug. 14, 1923.
*Hitchcock, Chas. H. Died Nov. 7, 1919.
*Holbrook, Levi. Died July 26, 1922.
*Holmes, Joseph A. Died July 13, 1915.
*Honeyman, David. Died Oct. 17, 1889.
*Hovey, Edmund O. Died Sept. 27, 1924.
*Hovey, Horace C. Died July 27, 1914.
*Howell, Edwin E. Died April 16, 1911.
Hunt, Thomas S. Died Feb. 12, 1892.
*Hyatt, Alpheus. Died Jan. 15, 1902.
Iddings, J. P. Died Sept. 8, 1920.
Irving, John D. Died July 26, 1918.
Jackson, Thomas M. Died Feb. 3, 1912.
*James, Joseph F. Died March 29, 1897.
Julien, Alexis A. Died May 7, 1919.
*Kemp, James F. Died Nov. 17, 1926.
Kennedy, William. Died Feb. 23, 1926.
Knight, Wilbur C. Died July 28, 1903.
Knowlton, Frank H. Died Nov. 22, 1926.
Lacoe, Ralph D. Died February 5, 1901.
Laflamme, J. C. K. Died July 6, 1910.
Lambe, L. M. Died March 12, 1919.
Langton, Daniel W. Died June 21, 1909.
*Le Conte, Joseph. Died July 6, 1901.
Lee, Willis T. Died June 17, 1926.
*Lesley, J. Peter. Died June 2, 1903.
Libbey, William. Died Sept. 6, 1927.
Loughridge, Robt. H. Died July 1, 1917.
McCalley, Henry. Died Nov. 20, 1904.
McGee, W J. Died Sept. 4, 1912.
McInnes, William. Died March 10, 1925.
Marcy, Oliver. Died March 19, 1899.
Marsh, Othniel C. Died March 18, 1899.
Mell, P. H. Died October 12, 1918.
*Merrill, Fred. J. H. Died Nov. 29, 1916.
Miller, Willet G. Died Feb. 4, 1925.
Mills, James E. Died July 25, 1901.
*Nason, Frank L. Died Sept. 12, 1928.
*Nason, Henry B. Died Jan. 17, 1895.
*Neff, Peter. Died May 11, 1903.
*Newberry, John S. Died Dec. 7, 1892.
Newsom, John F. Died Oct. 24, 1928.
Niles, William H. Died Sept. 12, 1910.
Norwood, Chas. J. Died Jan. 20, 1927.
*Orton, Edward. Died October 16, 1899.
*Osborn, Amos O. Died March, 1911.
*Owen, Richard. Died March 24, 1890.
Peck, Frederick B. Died Nov. 2, 1925.
Penfield, Samuel L. Died Aug. 14, 1906.
Penhallow, David P. Died Oct. 20, 1910.
Pirsson, L. V. Died Dec. 8, 1919.
*Platt, Franklin. Died July 24, 1900.

PETTEE, WILLIAM H. Died May 26, 1904.
*POWELL, JOHN W. Died Sept. 23, 1902.
*PROSSER, CHAS. S. Died Sept. 11, 1916.
*PUMPELLY, RAPHAEL. Died August, 1923.
PURDUE, A. H. Died Dec. 12, 1917.
RICE, WILLIAM NORTH. Died Nov. 13, 1928.
ROBINSON, HENRY H. Died Oct. 20, 1925.
ROGERS, G. S. Died Nov. 18, 1919.
*RUSSELL, ISRAEL C. Died May 1, 1906.
*SAFFORD, JAMES M. Died July 3, 1907.
SAINT JOHN, O. H. Died July 17, 1921.
*SALISBURY, ROLLIN D. Died Nov. 15, 1922.
*SCHAEFFER, CHARLES. Died Nov. 23, 1903.
SEELY, H. M. Died May 4, 1917.
SEÑA, J. C. DA COSTA. Died June 20, 1919.
*SHALER, NATHANIEL S. Died Apr. 10, 1906.
SLOAN, EARLE. Died Aug., 1926.
*SMITH, EUGENE A. Died Sept. 7, 1927.
*SMOCK, JOHN C. Died April 21, 1926.
*SPENCER, J. W. Died October 9, 1921.
SPRINGER, FRANK. Died Sept. 22, 1927.
*STEVENSON, JOHN J. Died Aug. 10, 1924.
SUTTON, WILLIAM J. Died May 9, 1915.
TARR, RALPH S. Died March 21, 1912.
TIGHT, WILLIAM G. Died Jan. 15, 1910.
*TODD, JAMES E. Died October 29, 1922.
TWITCHELL, M. W. Died Apr. 3, 1927.
UGLOW, WILLIAM L. Died Aug. 3, 1926.
*VAN HISE, C. R. Died Nov. 19, 1918.
VAN INGEN, GILBERT. Died July 7, 1925.
*VOGDVS, ANTHONY W. Died Feb. 8, 1923.
WACHSMUTH, CHAS. Died Feb. 7, 1896.
WADSWORTH, M. E. Died April 21, 1921.
*WALCOTT, CHAS. D. Died Feb. 9, 1927.
WATSON, THOMAS L. Died Nov. 10, 1924.
WELLER, STUART. Died Aug. 5, 1927.
WESTON, THOMAS C. Died July 20, 1910.
*WHITE, ISRAEL C. Died Nov. 25, 1927.
WHITE, THEODORE G. Died July 7, 1901.
*WHITFIELD, ROBT. P. Died April 6, 1910.
*WILLIAMS, GEORGE H. Died July 12, 1894.
*WILLIAMS, J. FRANCIS. Died Nov. 9, 1891.
*WILLIAMS, H. S. Died July 31, 1918.
WILMOTT, ARTHUR B. Died May 8, 1914.
*WINCHELL, ALEX. Died Feb. 19, 1891.
*WINCHELL, H. V. Died July 28, 1923.
*WINCHELL, NEWTON H. Died May 1, 1914.
WOODWARD, ROBT. S. Died June 29, 1924.
WOODWORTH, JAY B. Died Aug. 4, 1925.
WRIGHT, ALBERT A. Died April 2, 1905.
*WRIGHT, G. F. Died April 20, 1921.
YEATES, WILLIAM S. Died Feb. 19, 1908.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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PROCEEDINGS OF THE TWENTY-SEVENTH ANNUAL MEETING OF THE CORDILLERAN SECTION OF THE GEOLOGICAL SOCIETY OF AMERICA, HELD AT BERKELEY, CALIFORNIA, MARCH 2 AND 3, 1928.

RALPH W. CHANEY, *Secretary*

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Sessions of March 2 and 3

The twenty-seventh annual meeting of the Cordilleran Section of the Geological Society of America was held at Bacon Hall, University of California, Berkeley, on Friday and Saturday, March 2 and 3, 1928.

BUSINESS MEETING

ELECTION OF OFFICERS

A business meeting and luncheon was held at the Faculty Club, with seventeen Fellows of the Society in attendance. A Nominating Committee appointed by the Chairman, Robert van V. Anderson, proposed the following officers for the year 1929:

Chairman, BRUCE L. CLARK
Secretary, RALPH W. CHANEY
Councilor, F. L. RANSOME

The nominees were subsequently elected in a mail ballot conducted by the Secretary.

REPORT OF THE COMMITTEE ON PRIZES

The Committee on Prizes presented the following report:

1. The prize shall be awarded annually to a young man or woman, preferably a student who has not yet received his doctor's degree and who is under thirty years of age, who shall have presented to the Section the most satisfactory and the most important paper setting forth the results of his own research in geology.

2. Your committee has considered the award for the present year and has decided that the paper presented by Mr. Howel Williams, "Geology of the Marysville Buttes, California," is the most worthy, and therefore recommend that he be named by the Chairman of the Section as the prize-winner of the year.

ANDREW C. LAWSON,
J. P. BUWALDA, and
ELIOT BLACKWELDER.

Professor Lawson contributed $50 for the prize for the current year.

PRESENTATION OF PAPERS

The first session of the meetings was called to order by Chairman Robert van V. Anderson at 10 a. m. on March 2. A second session was held on the afternoon of the same day and two sessions were held on March 3.

The following papers were presented in the order indicated:

PITTSBURG BLUFF FAUNA OF THE OREGON OLIGOCENE

BY HUBERT G. SCHENCK

(*Abstract*)

One of the best preserved molluscan faunules in the Tertiary sandstones of the Oregon Coast Range is that at Pittsburg Bluff, Columbia County—the type locality of the well-known species, *Acila shumardi* Dall. Recently many of

the same species, equally well preserved, were collected from other localities in the State where stratigraphic relations are so clear that the position of the fauna has been established as being younger than Tejon Eocene and older than the Nye shale (lowermost Miocene or uppermost Oligocene) and therefore older than Temblor Miocene. Moreover, this fauna appears to represent the Lincoln-Porter horizon of the State of Washington. Some of the diagnostic species occur also in certain formations in California where Vaqueros (lower) Miocene is the superjacent and Tejon (upper) Eocene is the subjacent formation.

This paper was discussed by Mr. C. H. Crickmay.

PRELIMINARY STATEMENT REGARDING OREGON SHORELINE FEATURES

BY WARREN D. SMITH

Read by title.

REVISION OF THE GEOLOGY OF DEAD MAN ISLAND, CALIFORNIA

BY C. H. CRICKMAY

(*Abstract*)

It has become evident that the long established correlations of supposed Pliocene and Pleistocene deposits of Dead Man Island are contradictory and involved in some confusion. An anomalous condition appears to exist—cold water fossils were reported from beds which contained warm water ones. Application of strict faunal analysis resolves this problem and shows that in most cases cold and warm water shells do not occur in the same beds. This means that a greater number of fossil zones have to be recognized—an amplification of the stratigraphic record.

Discussion by Messrs. Willis, Clark, F. M. Anderson, Schenck, and the author.

WIND ABRASION IN THE ARID SOUTHWEST

BY ELIOT BLACKWELDER

(*Abstract*)

The work of the wind in the desert has two aspects—deflation and abrasion. This paper deals only with the latter.

The effects of abrasion upon rock surfaces may be divided into three stages: (*a*) polishing and pitting, (*b*) grooving, and (*c*) shaping and faceting. Effects of the first stage are very widespread throughout the arid regions, although of little consequence. Those of the second stage are much less common. The third stage is rare. It has been reached in only a few places, where strong winds, abundant sand, and absence of vegetation give the optimum conditions for the action of the sandblast.

Solution, even in the desert, causes pitted and fretted surfaces on limestones, and such markings have been ascribed to wind abrasion. Means of distinguishing the two phenomena will be discussed.

The topographic effects of the sandblast are slight but distinctive.

TECTONICS OF THE VALLE GRANDE AND SURROUNDING AREAS

BY BRUCE L. CLARK

(Abstract)

The Valle Grande, as defined in this paper, is the great negative area, which has existed throughout Mesozoic and Tertiary times and of which the present Great Valley of California is a remnant.

The following are some of the most important general conclusions as to the tectonics of the Valle Grande and surrounding areas:

1st. The Valle Grande originated as a complex fault trough; in general the western side of the basin was depressed more than the eastern. The faulting along the western side does not belong to one fault zone, but is formed by different faults, most of which along their southern extension disappear in the folded sediments of the Valle Grande. All these faults are believed to have had a pre-Cretaceous origin.

2d. The Coast Ranges to the west and the mountain blocks to the south of the Valle Grande have been positive throughout a large part of Mesozoic and Tertiary times. These general areas are broken by a series of primary faults, which had a very early origin and appear to be closely related. The result is that the Coast Ranges are divided into a series of blocks, each of which has had a somewhat different history. There have been different degrees of positivity and negativity on the different blocks, and in times of folding each was folded independently.

3d. All the folding in and around the Valle Grande is the result of compression on primary faults. The deposits in the western and southern margins of the basin have been folded up against the faults bounding it, and whatever folding is found out in the San Joaquin Valley is believed to be the result of compression on buried faults, which in all cases can be located in the marginal areas.

4th. Folding has been taking place along the western and southern margins of the southern portion of the Valle Grande since early Eocene times and probably earlier. It is a noteworthy fact that major unconformities and overlaps are found either on fault blocks or on the major anticlines, and that they are lost when we get away from these structures, from which we may conclude that the later folding has taken place on the same axes as the earlier.

Discussion by Messrs. Blackwelder and Weber.

HISTORY OF THE CHINLE TRIASSIC FORMATION IN THE SOUTHWEST

BY C. L. CAMP

(Abstract)

The main constituents of the lower Chinle, in the Painted Desert area, are Bentonites and bentonitic clays, grading upward into sandy shales and interstratified with lenses of sandstones and pebble conglomerates. Periods of volcanic activity followed by periods of rapid and then of normal deposition are indicated. The nature of the fossil deposits throws some light on the question of climatic conditions.

This paper was discussed by Messrs. Allen and Blackwelder.

SYMPOSIUM:

The following ten papers are contributions to the symposium:

The present status of geological problems of the Great Basin; Eliot Blackwelder, leader.

PRELIMINARY REPORT ON THE CRETACEOUS OF CENTRAL OREGON

BY EARL L. PACKARD

(Abstract)

Areas of Upper Cretaceous rocks occur at several localities along the flanks of the Ochoco Range of Central Oregon. The easternmost known locality lies high up on the range a few miles southeast of Dayville and the westernmost locality has recently been discovered by E. T. Hodge within the drainage basin of Deschutes River. The largest area lies within the Mitchell Quadrangle and has been mapped by J. P. Buwalda. The other fossiliferous areas along the range are of small extent, but they have yielded characteristic faunas not yet completely studied. The Mitchell anticline has yielded a large and varied ammonite fauna, one horizon being traceable for nearly the length of the structure.

Although final correlations have not yet been made, a part at least of the lower shales of the Mitchell anticline will probably prove to be of Horsetown age, while the coarser deposits higher in the section are undoubtedly of Chico age.

Discussion by Messrs. F. M. Anderson, Crickmay, and the author.

DISTRIBUTION AND CORRELATION OF THE TERTIARY FLORAS OF THE GREAT BASIN

BY RALPH W. CHANEY

Discussion by Messrs. Buwalda, Jones, and the author.

RESULTS OF GEOLOGICAL INVESTIGATIONS DURING RECENT YEARS IN NORTH-CENTRAL OREGON

BY JOHN P. BUWALDA

Following a brief review of previous knowledge, the following topics will be discussed: east-west folding in contrast to the north-south structures of the middle and southern Great Basin; three, perhaps more, periods of east-west faulting; changes in trend of axes of folding in successive periods; physiographic history of the region.

This paper was discussed by Messrs. Lawson, Louderback, and the author.

STRUCTURAL FEATURES DISPLAYED IN THE JOHN DAY AND DESCHUTES RIVER CANYONS

BY EDWIN T. HODGE

(*Abstract*)

This will describe investigations along the John Day and Deschutes rivers which reveal several major folds in the Columbia lava and other formations. These folds have been traced from the John Day to the Deschutes River canyons and thence into the Cascade Mountains. Fossils, stratigraphic, succession, and continuity of formation and structure display a column extending from the Cretaceous to the Recent. As a result of this discovery a new large area of fossiliferous John Day in the Deschutes Canyon and a new area of Cretaceous lying to the east of the Deschutes Canyon has been discovered.

Read by title.

OWYHEE PROJECT

BY WARREN D. SMITH

(*Abstract*)

This contains a discussion of the structural features of the dam site and reservoir site of the Owyhee project, on the Owyhee River, in the extreme eastern portion of Oregon. The particular interest attached to this project is that this dam will be the highest dam in the world when completed—368 feet high. The dam will abut on a rhyolite formation of presumably Clarno-Eocene age. This is very completely fractured by five major sets of joints, so that grouting on a large scale will have to be resorted to. There is evidence of some faulting in this vicinity. The country rock in the reservoir is a tuff of presumably Oligocene age. Dipping away from the reservoir itself, these introduce other factors of more or less serious import into the situation.

DIATOMACEOUS DEPOSITS OF EASTERN OREGON

BY WARREN D. SMITH

(*Abstract*)

This report is a preliminary statement conerning the important diatomite deposits of eastern Oregon, which are of commercial importance, the one at Harper, in the extreme eastern portion of the State, being dealt with in greater detail. That near Terrebonne, on the Deschutes River, is the second one. The character of the diatoms in these two deposits is quite different; all species are fresh-water forms. This material finds use in three important lines of industry: as an insulating building material; for purpose of filtration in oils and sugars; and for mixing with cement in concrete. As the deposit at Harper is larger than the well-known celite deposit of California, considerable interest will eventually be developed in this material.

Discussed by Mr. Donnay and the author.

INVESTIGATIONS IN VERTEBRATE PALEONTOLOGY IN THE GREAT BASIN

BY CHESTER STOCK

Discussion by Messrs. Matthew, Buwalda, Clark, and the author.

AGE OF LAKE LAHONTAN

BY J C. JONES

(*Abstract*)

A further study of the deposition of salts in arid basins indicates that thick layers of salts can not form or be buried, as has been supposed. Data accumulated indicates that the content of salt present in the existing remnant lakes of Lake Lahontan gives a fairly accurate clew to the age of Lake Lahontan. The finding of an extinct camel and a modern big-horn sheep in the Walker Lake basin and a buffalo skull in a Lahontan bar near Lovelock indicates the transition from the Pleistocene fauna to the Recent fauna took place during the existence of Lake Lahontan.

Discussion by Messrs. Weber, Willis, Sauer, Blackwelder, Engel, and the writer.

ORIGIN OF THE PIEDMONT PLAINS OF THE GREAT BASIN

BY ELIOT BLACKWELDER

(*Abstract*)

It is generally understood that in the arid Southwestern States the mountain ranges are flanked by inclined plains (bajadas) that consist of alluvial deposits in the form of coalescing fans. In parts of Arizona and Sonora, on the other hand, it has been shown that such plains are generally eroded surfaces underlain by solid rock. These have been termed pediments.

Pediments and bajadas (fans) are both made by torrential streams from mountain canyons. They resemble each other in general appearance and in having stream profiles that are slightly concave upward. They differ not only in that the pediment consists chiefly of rock, whereas the fan consists of gravelly detritus, but the fan has a notably convex transverse profile, whereas the pediment has a nearly level profile parallel to the range front. The gradients of the bajadas average somewhat steeper than those of the pediments. The difficulty of discriminating the two features is due partly to the fact that many pediments are strewn with a thin layer of gravel, and partly to the fact that many of them, on account of recent climatic changes and gentle warpings, have alluvial fans superposed on their eroded surfaces. Such composite plains are common in the Great Basin Province.

The writer finds that the pediment, instead of being abnormal and restricted to certain localities, is widespread throughout our desert region and is the type of plain normally developed during quiescent periods. Alluvial fans, on the other hand, probably can not be made under static conditions. They are built where normal gradients have been changed by faulting, warping, lateral erosion, or other special causes. Fans made in response to cli-

matic change are probably thin, but very common. It is believed that thick alluvial fan formations can be deposited only in a region of active diastrophic movements.

This paper was discussed by Mr. Jones and the author.

OWENS VALLEY REGION

BY C. F. TOLMAN

(*Abstract*)

The geology of the east front of the Sierra Nevada and adjacent parts of the Great Basin will be discussed.

Read by title.

At the conclusion of the symposium, the presentation of general papers was resumed.

NATURE OF THE FIRST MOTION OF TWO EARTHQUAKES

BY PERRY BYERLY

(*Abstract*)

The seismograms of the Chilean earthquake of November 11, 1922, show that the first motion recorded at the South African stations, Good Hope and Johannesburg, and at Batavia, in Java, was a rarefaction, while at all stations in other directions (that is, stations bearing between north 50 degrees east and north 143 degrees west) the first motion was a compression. An adaptation of the theoretical work of Nakano shows that this distribution could be caused by a single force applied at the focus and acting in a direction between north and north 55 degrees west, with a dip between 3 and 18 degrees.

The first motion due to the Montana earthquake of June 25, 1925, was a compression at Saskatoon, Canada, and at Zi-Ka-Wei, China, and a rarefaction at all stations in other directions (that is, at stations bearing from north 33 degrees east southerly to north 71 degrees west from the epicenter). The nature of the forces acting at the focus in this case was more complicated. Two forces acting inward at the focus, making an angle with each other of between 76 degrees and 113 degrees in a plane nearly horizontal, and with a resultant directed between north 3 degrees west and north 22 degrees west. would be sufficient to cause such a distribution.

Discussed by Mr. Buwalda.

MECHANISMS OF UPLIFT AND SUBSIDENCE

BY BAILEY WILLIS

This paper was discussed by Messrs. F. M. Anderson, Clark, R. V. Anderson, Jones, and the author.

CLEAVAGE VERSUS PARAJOINTING

BY JOSEPH D. H. DONNAY [1]

(*Abstract*)

A brief discussion of the different structures referred to under the name of rock cleavage, with special emphasis laid on the important discrimination between cleavage proper and false cleavage, also called respectively flow cleavage and fracture cleavage (Leith, 1905). Attention will be concentrated on the present terminology, which leads to confusion.

The deficiency of the nomenclature, together with the fundamental differences in the origin of the two mentioned structures, seems to justify the coining of a new term to designate the "closely spaced tight joints giving the rock a capacity to part along parallel surfaces."

The word "parajointing" is proposed.

INTRUSIVE ROCKS IN THE KLAMATH MOUNTAINS, NORTHERN CALIFORNIA

BY N. E. A. HINDS

(*Abstract*)

In the Klamath Mountains is a group of plutonic and hypabyssal intrusives which apparently belong in part at least to the Sierra Nevadan period of batholithic invasion. Most of these bodies cut pre-Triassic rocks, a few the Triassic, while certain small offshoots intrude the Jurassic. Whether more than one period of intrusion is represented has yet to be determined.

North of Redding is a great, irregular interformational dike of quartz-augite diorite about 20 miles long, which throughout most of its extent separates the Pennsylvanian McCloud limestone from the underlying Mississippian slates or igneous rocks. More or less intense metamorphism has taken place along the limestone contact and an extensive series of contact minerals has been developed. Locally small bodies of magnetite are present along or near the limestone contact. The metamorphism of the slates and igneous rocks is generally not conspicuous.

The other plutonic bodies are stocks of various sizes, composed of granodiorites or quartz diorites; these intrude Mississippian and Devonian sediments and igneous rocks, serpentines, and other formations of undetermined ages. Prominent contact aureoles are common in the slate. Along the serpentine contacts, hybrid rocks, generally gneissic or schistose in texture, are locally present. The metamorphism of the igneous rocks is rarely conspicuous. Certain peculiarities in the composition of the intruding rocks along the contacts suggest the assimilation of country rock.

Two hypabyssal intrusives of rudely laccolithic form are present in the Redding and Weaverville districts. Diller interpreted these as extrusives, but Graton and others have fully demonstrated their intrusive character. The Bully Hill body cuts Triassic formations; the Balaklala mass to the west cuts Devonian or older rocks. Both apparently are contemporaneous. The Balaklala intrusive appears to be transitional into a highly quartzose diorite stock with which it is closely associated.

Small dikes and sills, offshoots from the larger bodies, are common.

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[1] Introduced by Dr. E. Blackwelder.

USE OF FORMATION CONTOURS IN GEOLOGIC MAPPING

BY W. S. TANGIER SMITH

(*Abstract*)

This paper describes a method of using formation contours, in connection with the mapping of formation boundaries, to bring out geologic structure and also to check the accuracy of the mapping.

MORAINES OF CONVICT LAKE GLACIERS

BY ELIOT BLACKWELDER

(*Abstract*)

Along the east side of the Sierra Nevada Mountains between Mono Lake and Owens Lake, several Pleistocene glaciers issued from the canyons and left moraines on the adjacent plains. Near Convict Lake moraines of two distinct epochs are readily distinguished by the notable differences in the effects of weathering and erosion. During the interglacial epoch the creek excavated a spacious valley in the north flank of the largest moraine. Being deflected by this valley, the later glacier pushed its way entirely through the old moraine and built a conspicuous terminal lobe outside the latter. There is, perhaps, no place in California where the contrast between the moraines of the last two glacial epochs is more clearly visible than at Convict Lake.

Discussion by Messrs. Lawson, Jones, Packard, and the author.

STRUCTURES IN THE VICINITY OF SANTA CRUZ

BY KARL RODE

(*Abstract*)

The bedrock complex of Ben Lomond Mountain, north of Santa Cruz, consists of various schists, marble, and granitic to granodioritic intrusions. The diastrophism and metamorphism of the schistose rocks and the marble partly antedate the intrusions. The local strike and dip of the schistosity does not conform to any general trend, but the axes of minor synclines and anticlines strike slightly north of west. A locally occurring linear structure of crystalloblastic character and the parallel arrangement of the prismatic minerals in the granodiorite emphasize the significance of this direction. The dip of the linear element is generally in accordance with the inclination of the Tertiary and post-Tertiary deformation, but steeper. This suggests the long endurance of the same upward tendency.

GEOLOGY AND MINERALIZATION AT PACHUCA, MEXICO

BY CARLTON D. HULIN

(*Abstract*)

The silver veins of Pachuca, ninety-three kilometers northeast of Mexico City, were discovered by Cortez and his followers in 1534.

The rocks of the region consist entirely of volcanics and are unquestionably of Tertiary age, resting presumably on Lower Cretaceous marine sediments.

The following chief subdivisions have been recognized in the volcanic series:

Top.	Basalt flows	40 meters
	Unconformity.	
	Dacite series	100+ meters
	Unconformity.	
	Rhyolite series	150+ meters
	Unconformity.	
	Purisima series	400+ meters
	Unconformity.	
	La Rica series	1,070+ meters
Bottom.	Fortuna series	375+ meters

The various horizons consist chiefly of lava flows, though flow-breccias, agglomerates, and tuffs are all strongly represented. The flows up to and including the Purisima series consist almost entirely of andesites.

The Purisima series and all older horizons over most of the region dip at moderate angles to the northeast, while the rhyolites and later groups dip at low angles to the south.

Intrusions of dacite, rhyolite, and diabase, the latter known only in the north part of the district, cut all horizons, including the rhyolites and the lowermost members of the dacite flow series. These intrusions are chiefly dikes, though a few small stocks are represented.

Faulting commenced at the close of the outpouring of the La Rica series and continued intermittently until the earlier flows of the dacite group, apparently reaching maximum activity during the extrusion of the rhyolite flow series.

The dominant faults of the region strike in the northwest quadrant and show evidence of both horizontal and vertical movements. Normal and reverse displacements are both represented. Two secondary fault systems are also developed, one, in the vicinity of Pachuca, striking east and west, and the second, in the vicinity of Real del Monte, striking north and south.

The veins of the region are distinctly of the shallow or epithermal type and have been formed almost entirely through the filling of fault fissures. Economic metals are limited to silver with a mere trace of gold.

The mineralization occurred shortly after the intrusion of the rhyolite dikes. The early stages of the mineralization consisted almost entirely of the deposition of barren quartz. During the late stages there was introduced rhodonite, bustamite, carbonates (chiefly calcite), pyrite, sphalerite, galena, chalcopyrite, and, last of all, the silver, chiefly as argentite.

The location of the ore shoots was directly controlled by local structure and by fault movements acting contemporaneously with the mineralization. The early vein fissures were filled by barren quartz. These early veins remained barren except where the local structure was such that intermineralization movements produced brecciation and reopenings of the veins, resulting in the production of avenues of passage and sites of deposition for the silver-bearing solutions.

Zonal control of the silver deposition is strongly manifest at Pachuca. Following the silver deposition there existed in the veins between the surface and

the top of the economic silver ore a barren zone which approximated 400 meters in thickness. While in parts of the region erosion has cut down to the silver zone, over much of the area considerable remnants of the barren zone still overlie the productive portions of the veins.

While effects of oxidation in place are prominent in the veins to depths below the present surface as great as 700 meters, no noticeable concentrations of ore occur which can be attributed to secondary enrichment.

NEOCENE EROSION SURFACE IN CENTRAL OREGON

BY JOHN P. BUWALDA

(*Abstract*)

At least two cycles, or subcycles, of erosion are represented in the physiography of central Oregon. In the earlier cycle a surface, ranging in stage from old age to peneplain, was cut across the folded Columbia lava and overlying Mascall formation. The middle Pliocene Rattlesnake formation apparently lies upon this surface. Remnants of the surface remain in the drainage basin of the John Day River, and extensive areas have been well preserved on the south slope of the Ochoco Mountains south and southeast of Mitchell. From these areas it is given the name Ochoco erosion surface. Its age is lower or middle Pliocene.

During the last erosional episode, still in progress and termed the Dayville subcycle, the steep-walled canyons and open valleys in soft sediments were and are being carved.

Comments were made on this paper by Mr. Jones.

CAVERNOUS WEATHERINGS IN ARID REGIONS

BY ELIOT BLACKWELDER

(*Abstract*)

In arid regions igneous rocks are often weathered into cavernous forms that have been variously ascribed to the action of wind, rain, and solution. This paper interprets them as the effects of a complex process in which expansion due to the hydration of silicate minerals causes disintegration of the rock. Such action proceeds more rapidly in shaded recesses and under the surface than on the drier exteriors. Thin scales of rock and loose crystals separate from the walls of the cavities and fall to the bottoms. The loose debris from this exfoliation is removed by various agencies, among which the wind is probably the most important, although rainwash and the activities of such animals as rodents and lizards are important.

MAUI VOLCANO, HAWAII

BY N. E. A. HINDS

(*Abstract*)

The Maui volcano is the largest in the windward section of the Hawaiian Range. Its exposed summits are the two forming the Island of Maui, the two of Molokai, and the single domes of Lanai and Kahoolawe. Extending west-

ward from West Molokai is the slightly submerged Penguin Bank; this probably was an island which long since has been eroded or has subsided below sealevel. The Maui volcano is separated from Hawaii by a channel 30 miles wide and 10,000 feet deep. Between the Penguin Bank and Oahu the channel is 9 miles wide and about 2,300 feet deep; the submarine connection between the Maui volcano and Oahu, therefore, is much closer than with Hawaii. It is probable that Oahu and the Maui volcano were originally isolated mountains which have been united below sealevel by the overlapping of lavas coming from East Oahu and from some center on the second mountain, possibly represented by the Penguin Bank.

On Maui the western dome is the older and more greatly dissected. East Maui is a young dome, which has been extinct long enough for deep gorges to have been cut into its windward (northeastern) slopes. The leeward side has suffered little erosion. At the summit of East Maui is a great faulted depression breached by narrow grabens in two places. Some of the most recent eruptions have taken place within this depression.

Molokai also is a volcanic doublet. The western member is the older, but, because of its low elevation and consequently arid climate, has not been so deeply eroded as the eastern dome. The northern half of the eastern dome has disappeared as the result of profound engulfment. The existing remnant has been deeply scored by fluvial and marine erosion, especially on its windward (northern) side.

Lanai and Kahoolawe each are composed of a single dome. Like West Molokai, they are of low elevation and receive little rainfall. Lanai should be more heavily watered, but is protected from the trade wind rains by the great bulk of Maui to the east.

Discussion by Messrs. W. D. Smith and Louderback.

PROGRESS REPORT ON INVESTIGATIONS OF DIATOMACEOUS EPIDEMICS AND DIATOMACEOUS OIL

BY C. F. TOLMAN, T. HASHIMOTO, AND L. A. THAYER

Read by title.

GEOLOGY OF THE MARYSVILLE BUTTES, CALIFORNIA

BY HOWEL WILLIAMS

(*Abstract*)

The isolated Marysville buttes lie near the center of the Sacramento Valley, forming a circular group ten miles in diameter. They consist essentially of three more or less concentric divisions:

(*a*) A central core of andesite, four miles across.
(*b*) A peripheral ring of andesite tuff and breccia.
(*c*) An interior ring of upturned sedimentary rocks.

The sedimentary rocks range from Chico (Cretaceous) to Pliocene in age and include a thick development of Meganos (Middle Eocene) beds. These sediments were upturned by the intrusion of the central core or laccolith. In

addition to suffering a general doming, they were broken by faults, disposed both radially and concentrically with respect to the laccolithic margins. The radial blocks were tilted outward at various angles and occasionally to verticality. The top of the laccolith was very irregular and was covered by only a thin sedimentary roof. During the Pliocene this roof was almost entirely removed, and the sediments had been eroded almost to their present elevation when a series of intrusions of rhyolite porphyry occurred both under the laccolith and among the enclosing sediments. These intrusions disturbed the sediments still further and gave rise to violent steam explosions that blasted a crater a mile in diameter through the center of the laccolith. From four to six cubic miles of andesite tuff and breccia were erupted at temperatures which have been determined experimentally to have been less than 800 degrees centigrade. The ejecta were entirely solid and unaccompanied by the explosion of fresh magma. Recent erosion has exposed the pre-eruption surface of many of the sedimentary hills.

Discussion by Messrs. Lawson, Louderback, Blackwelder, R. Anderson, Engel, and the author.

WALLOWA MOUNTAINS

BY WARREN D. SMITH

IONE FORMATION OF CALIFORNIA

BY VICTOR T. ALLEN

(Abstract)

The name Ione formation was given by Lindgren to the clays and sands deposited along the Great Valley of California during the "Neocene" period, while the auriferous gravels accumulated on the slopes of the Sierra Nevada Mountains. Turner made three divisions of the Ione formation at the type locality. In ascending order these are: (*a*) white clays and sands containing lignite; (*b*) white or red sandstone; (*c*) clay rock or tuff. In the present paper it is proposed to restrict the term Ione formation to the beds along the Sierra Nevada foothills having a similar mineral composition and history to the two lower divisions of the type locality. These sediments consist of quartz-anauxite sands and clays that are composed of minerals resistant to chemical weathering. The mineral assemblage is so definite and characteristic that it has been traced from Oroville to Daulton, a distance of 200 miles, along the foothills of the Sierra Nevada. Used in this limited sense, the formation becomes an important horizon, valuable in correlation.

At a number of places, including the type locality, the Ione formation rests on a lateritic surface consisting in part of oolitic iron-aluminum hydrates, but mostly of white lithomarge retaining the structure of the rocks from which it was derived. This surface was formed by weathering under tropical or subtropical conditions during the Eocene. The structures of the Ione sediments, including channel-filling, ripple-marks, cross-bedding, and lenses of gravels and their close association with recognized stream deposits, indicate

the Ione formation to be a delta deposit formed at the mouths of many westward flowing streams. The white quartz gravels, among the "auriferous gravels of the Sierra Nevada," have a mineral assemblage similar to that of the Ione, and their stratigraphic relations suggest them to be contemporaneous. The streams of this period eroded the surface weathered during the Eocene, and carried clays, sands, and gravels from which the easily decomposed minerals had been removed, westward to form deltas. The occurrence of *Turritella merriami* Dickerson in the Ione and a larger fauna above and below the Ione at the Marysville Buttes are considered by Dr. Bruce L. Clark to suggest that the Ione is of Middle Eocene (Meganos) age.

The "clay rock," an altered rhyolitic tuff, the uppermost member of Turner's section, is separated from the lower members by an unconformity representing a long period of erosion. It should not be considered a part of the Ione formation, but belongs to the rhyolite tuff series. This series, mapped separately in places by Turner, is of later age, possibly Miocene.

Discussion by Mr. Rogers.

PLEISTOCENE ELEPHANT ON SANTA ROSA ISLAND, CALIFORNIA

BY CHESTER STOCK AND E. L. FURLONG

(*Abstract*)

The occurrence of elephant remains in Pleistocene deposits on Santa Rosa Island was recorded as early as 1873. Recent paleontological investigations conducted by the California Institute of Technology on this member of the Santa Barbara Islands has yielded further remains of Proboscidea. The occurrence and nature of the materials are described and their significance indicated.

Discussion by Messrs. Hall, Chaney, Matthew, R. V. Anderson, Louderback, and the author.

D 'IMITATION OF JURA AND TRIAS IN BRITISH COLUMBIA

BY C. H. CRICKMAY

(*Abstract*)

Two areas were studied stratigraphically in detail, one on the British Columbia coast, the other in the interior. At the former, earliest Lias beds lie conformably on the Upper Noric. At the latter, earliest Middle Jurassic lies unconformably on the Noric.

Discussion by Mr. Lawson and the author.

AGE OF THE DALLES BEDS AND THE "SATSOP" FORMATION AND HISTORY OF THE COLUMBIA RIVER GORGE

BY JOHN P. BUWALDA AND BERNARD N. MOORE

(*Abstract*)

Vertebrate fossils and other evidence indicate that The Dalles Beds are approximately Middle Neocene in age. From its relation to The Dalles Beds

the "Satsop" of the Columbia River Gorge is of equivalent or greater age, and not the correlative of the Quaternary Satsop of the Oregon and Washington coasts. The "Satsop," now renamed "Hood River Formation," was folded with the underlying Columbia lavas during the uplift of the Cascades and the cutting of the gorge. The gorge, because of the newly established greater age of the "Satsop" and other considerations, has not been excavated entirely since some date in the Quaternary, as heretofore held by some writers. The uplift and transsection began some time in the Pliocene.

ANNUAL DINNER

The annual dinner was held under the auspices of the Le Conte Club, on Friday evening, at Stephens Union. Sixty-four Fellows and guests attended the dinner, which was followed by an interesting outline of the geology and geography of Australia by Professor Andrew C. Lawson.

REGISTER OF THE 1928 MEETING

FELLOWS

F. M. ANDERSON
ROBERT V. ANDERSON
ELIOT BLACKWELDER
JOHN P. BUWALDA
RALPH W. CHANEY
BRUCE L. CLARK
OSCAR H. HERSHEY
J. M. HILL
J C. JONES
ANDREW C. LAWSON
AUGUSTUS LOCKE
GEO. D. LOUDERBACK
W. D. MATTHEW
F. L. RANSOME
A. F. ROGERS
HUBERT G. SCHENCK
S. SHEDD
WARREN D. SMITH
W. S. TANGIER SMITH
CHESTER STOCK
BAILEY WILLIS
W. P. WOODRING

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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PROCEEDINGS OF SECTION E OF THE AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

GEORGE R. MANSFIELD, *Secretary*

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Joint Sessions of Section E and the Geological Society of America

Section E of the American Association for the Advancement of Science held a joint session with the Geological Society of America at the American Museum of Natural History, New York, on December 26, 1928, Frank Leverett, Vice-President of the American Association for Section

E, presided. The retiring chairman was Charles Schuchert. His address, entitled "Geological history of the Antillean region," was read, in his absence, by C. O. Dunbar, at a joint session of the two bodies, December 28, Bailey Willis presiding.

"Geology Day," so designated by President Osborn, of the American Association, was observed December 27 by the presentation of a symposium, "The centenary of the glacial theory," before a joint session, with Henry Fairfield Osborn as chairman. Six geologists participated.

In the evening of the same day Charles P. Berkey gave a popular address before a general session of the Association, entitled "Recent discoveries in the geology of Mongolia."

A small geological exhibit in the Hall of Education was prepared especially for this day, on invitation of President Osborn.

The following papers were read or presented by title at the joint session on December 26, chiefly by non-members of the Geological Society:

TITLES AND ABSTRACTS OF PAPERS

THERMAL SPRINGS NEAR THE WASATCH FAULT

BY STERLING B. TALMAGE[1]

(*Abstract*)

A score or more of thermal springs occur near the west face of the Wasatch Range. Twelve of the more important of these springs were studied in the field and samples of the waters examined in the laboratory.

The four springs, within ten miles of Utah Lake, are all fresh to the taste; the total solid content ranges from 470 to 1,560 parts per million and the temperatures range from 19 to 59 degrees centigrade.

The six springs north of Salt Lake City, between the Wasatch Mountains and the Great Salt Lake, are all saline; the total solid content ranges from 4,470 to 40,850 parts per million and the temperatures range from 20 to 56 degrees centigrade. The springs near Salt Lake City carry some hydrogen sulphide, as does the spring at Castilla, in Spanish Fork Canyon, in the southern part of the Wasatch Range. The springs near Ogden precipitate out some iron oxide. In some cases a hot spring has a cooler spring near by. Chemical similarities indicate that these are cases of dilution by ordinary ground water. The chief saline constituent is sodium chloride.

Some of these springs occur right on the line of the Wasatch fault; these are all hot and saline. Some come from the piedmont alluvium below the fault line; these are hot or cool and fresh or saline. Some come from the Lake Bonneville sediments, so far west of the fault as to make the relation doubtful; these are hot, either fresh or saline.

These waters are probably of meteoric origin, heated by contact with hot rocks at depth. The depths required are probably less than the average thermal gradient would indicate, on account of heat developed by friction on the recently active fault surface.

[1] Introduced by U. S. Grant.

GEOLOGY OF THE VERTEBRATE FOSSIL LOCALITY AT MARAGHA, PERSIA

BY EUGENE CALLAGHAN [1]

(*Abstract*)

The region in northwestern Persia east of Lake Urmia and including the cities of Tabriz and Maragha is of considerable interest because the Pliocene deposits there contain a fairly extensive vertebrate fauna. The best collecting ground is ten miles east-northeast of Maragha.

The Mount Sahend Range, in the central part of the area, is an elongate mountain mass of deeply dissected lava flows resting upon folded and eroded Mesozoic limestones and shales. On all sides of this center but the west are extensive dissected Pliocene alluvial fan deposits composed of volcanic detritus. At the southern side of the area these deposits end against a range of Mesozoic limestone and shale and on the north and east are cut off by peripheral valleys or covered by later alluvium.

North of one of these valleys at Tabriz are Upper Miocene red gypsum-bearing conglomerates and sandstones grading into red and gray shales, the latter containing lignite seams. These beds have been somewhat crumpled and are sharply tilted to the south.

Immense travertine deposits rest on the Mesozoic limestones which outcrop with their associated shales between the volcanic area and Lake Urmia. Many of the travertine hills are deeply eroded, but in limited localities there is active spring deposition.

Brief remarks were made by Messrs. Henry Fairfield Osborn and William B. Scott.

PLIOCENE DEPOSITS OF CENTRAL MONGOLIA

BY LESLIE ERSKINE SPOCK [2]

(*Abstract*)

During the 1928 field season the Central Asiatic Expedition of the American Museum of Natural History, exploring to the east of the Urga-Kalgan trail, encountered Pliocene beds containing a rich and unusual fauna. The beds have been termed the Tung Gur formation, from the first discovered and most prolific locality, which lies about 46 miles east of Iren Dabasu. The lithology and structure of the beds indicate that they are for the most part of lacustrine origin, and there is good evidence to the effect that the animals were lake-shore dwellers. The most outstanding fossil discovered is a mastodon of unusual type. The Pliocene beds of the region cover several thousand square miles and in their maximum development are at least 500 feet thick.

Brief remarks were made by Messrs. Henry Fairfield Osborn and William B. Scott.

---

[1] Introduced by Charles P. Berkey.

[2] Introduced by Charles P. Berkey.

HEAVY MINERALS OF THE UPPER CAMBRIAN FORMATIONS OF MINNESOTA

BY W. A. P. GRAHAM [1]

(*Abstract*)

Difficulty in correlation of the Cambrian formations of Minnesota and Wisconsin led to the study of the heavy minerals they contained. The minerals studied were garnet, topaz, rutile, anatase, apatite, cyanite, and tourmaline. These minerals contained inclusions of rutile, apatite, zircon, and others. Great similarity in the distribution of the heavy minerals, as well as in the inclusions in these minerals, was found throughout the Cambrian formations. Correlation on this basis, therefore, is not practical. The failure of petrographic correlation in the Cambrian of this region is thought to be due to the uniformity of the rock types furnishing the Cambrian sediments.

PRIMARY STRUCTURE OF THE ADIRONDACK ANORTHOSITE

BY ROBERT BALK [2]

(*Abstract*)

Toward the contact the massive anorthosite develops commonly a border phase which varies in chemical composition and has been described by many authors. This border phase is deformed, either by platy (foliation) or by linear parallelism (flow-lines, stretching). The deformation may render the rock extremely schistose and the minerals may be drawn out into long streaks. The deformation is older than pegmatites and a part of the garnets of the rock. The marginal foliation dips gently away from the anorthosite, the linear parallelism coincides approximately with the dip of the foliation. In the southeast and north, Grenville sediments along the contact zone are gently upturned toward the anorthosite. Their attitude and the marginal structures of the anorthosite indicate that the intrusive has domed the crust upward, whereby its rim grew schistose due to friction and retardation along the walls. Where the walls project and the passage for the magma was constricted (zone Ausable Forks-Schroon Lake) the deformation is particularly strong and the foliated border very broad.

Apart from the contact, the anorthosite develops a rim facies and becomes foliated only in the vicinity of gabbros. In twenty-seven examined cases, the foliation of the anorthosite dips under the gabbros. The Jay Mountain gabbro (Ausable Quadrangle) contains thick layers of border facies anorthosite lying nearly horizontal between conformably foliated gabbro. A gabbro east of Green Mountain (Elizabethtown Quadrangle) is interbedded with the border phase along its gently inclined floor. Labradorite phenocrysts may appear within the gabbros, and the surrounding anorthosite grows frequently more basic. The examined gabbros are considered older or of approximately the same age as the anorthosite; no contrary field relations have been found, as described by other authors, from adjacent areas.

South and northwest of Elizabethtown the anorthosite seems to grade into syenitic rocks. Sharp boundaries are sometimes lacking. A network of

[1] Introduced by Frank F. Grout.
[2] Introduced by Charles P. Berkey.

syenitic veins and apophyses traverses the anorthosite, leading to normal syenites with labradorite phenocrysts on one side and normal anorthosite on the other.

The field relations favor the assumption that a large volume of magma rose which was rich in labradorite crystals. Basic minerals seem to have gathered first (gabbros), retarding the movement of the surrounding magma and causing the synclinal foliation of the anorthosite surrounding them. Most of the labradorite crystals have probably gathered next, becoming slower than the more acidic constituents of the magma (syenites). The latter seem to have moved farther outward from the general vent. The field study indicates that crystal settling is compatible with a general upward movement of the whole volume of magma. Gabbros settle with reference to the main anorthosite, and the latter appears to be more inert than the remaining syenitic magma, although it, too, rises with reference to the country rock.

The preliminary report is based on seven months' field-work, and the work is to be continued.

Brief remarks were made by Prof. George H. Chadwick.

JOINT STUDIES IN THE OUACHITA MOUNTAINS AND INTERIOR PLAINS OF OKLAHOMA [1]

BY F. A. MELTON [2]

(*Abstract*)

The most prominent of the joint systems in the Pennsylvanian and Permian sedimentary rocks of the central plains of Oklahoma radiate from the front of the Ouachita Mountains. The joints were formed at the time the folding of the mountains began; and, since they are found in beds of middle Permian age, this folding is known to have been accomplished, at least in part, later than middle Permian time.

The direction of this joint system correlates closely with the prevailing strike of the individual faults in the *en échelon* fault belts of central Oklahoma. The latter are thus connected with the Ouachita Mountain folding, to which they probably owe their origin. It is suggested that the *en échelon* alignment of these faults into north-south trending belts, parallel to the strike of the strata, is more apparent than real, due to the concentration of detailed field mapping on the sharp contacts of relatively thin persistent strata. Large areas of shale and sandstone doubtless are cut by similar faults the recognition of which is difficult because of their location. The presence of "master faults" in the basement complex is thus believed to be discredited.

NATURAL MOUNDS OF SOUTHERN ARKANSAS, NORTHERN LOUISIANA, AND EASTERN TEXAS

BY F. A. MELTON

(*Abstract*)

The chief hypotheses which have previously been offered are reviewed, and new evidences, drawn from aerial photographs and field observation, are

[1] Published with permission of the Oklahoma Geological Survey.
[2] Introduced by R. T. Chamberlin.

utilized to make a careful selection of these hypotheses. The conclusion is drawn that the so-called "natural mounds" of the area studied owe their origin to gullying by small streams and rivulets in a very weak, sandy soil. The name "residual soil hillocks" is suggested to replace the misleading term so long used.

These papers were read by title in the absence of the author.

STAGES IN THE STRUCTURAL EVOLUTION OF EASTERN ASIA

BY GEORGE B. BARBOUR[1]

(*Abstract*)

The foundations for the study of the tectonic development of Asia were firmly laid by Suess. Notable advances in an understanding of the continental structure are due to v. Richthofen, Willis and others. Through the recent work of Berkey, Grabau, Gregory, Morris, Mushketov, Obruchev, Teilhard, Wong, and others, new data are available for a more detailed analysis which in the main confirms the general sequence of events as stated by Willis and Hobbs. The present paper reviews the main stages in the evolution of the area of Asia lying east and north of the Himalayan fold-belt.

Using as a base paleogeographic maps of Grabau for each of the critical periods, the successive zones of folding are traced and related to the geosynclines on whose sites they rose, and to the position of the older reduced fold-ranges or the continental elements to whose margins they conformed. The effects of Paleozoic thrusting were mainly taken up in the heart of the continent. With the gradual welding of the central mass the zones of buckling shifted toward the present margin, compressional stresses died out in the interior where folding gave place to faulting and warping, with a corresponding change in the character of the igneous activity. There is a distinct general conformity between the older and younger "leitlinien," divergence from earlier trends being most marked in the case of the younger tensional fault-lines. There is a sharp difference in the grade of dynamic and regional metamorphism affecting rocks above and below the major unconformities (especially the Upper pre-Cambrian and Middle Mesozoic breaks); but, with certain localized exceptions, there is in the Far East usually no marked change of fold-axis distinguishing "plis du fond" and "plis de couverture."

THRUST FAULTS OF THE ROANOKE AREA, VIRGINIA

BY HERBERT P. WOODWARD[3]

(*Abstract*)

Roanoke County, Virginia, in the central portion of the Great Valley of Virginia, is an area exhibiting a complexly faulted structure. The low angles of the planes of these faults and a slight warping subsequent to the faulting have produced, under continued erosion, a very sinuous pattern in the

[1] Introduced by Charles P. Berkey.
[2] Published by permission of the Virginia Geological Survey.
[3] Introduced by Charles P. Berkey.

traces of many of the overthrusts, with the attendant production of fensters, outliers, and klippen.

An interesting portion of this area lies about ten miles northeast of Roanoke, where parts of three overthrust masses may be observed overlapping each other. The oldest appears at the surface through a fenster which lies within a mile of an outlier of the youngest fault-block. The three overthrust masses are distinguishable by the juxtaposition of dissimilar parts of a thick and easily recognizable stratigraphic series, as well as by their anomalous positions. At this point the lowest visible block contains a portion of an anticline which appears as a fenster through the northeastern margin of the great Catawba syncline, which in turn is overlain by a partially isolated remnant of the anticlinal structure associated with the Blue Ridge overthrust. The latest of the faults involved is the Blue Ridge fault whose block rests upon that of the Pulaski fault. This block similarly overlaps an older mass which itself probably covers other fault blocks.

The stripping off of the overthrust block of the Blue Ridge fault has greatly widened the valley at this point, adding to it the valleys of Goose and Glade creeks in Botetourt and Bedford counties, both of which are breached fensters. Erosion of the second fault block has produced an island of Siluro-Devonian rocks rising through and entirely surrounded by Cambrian and Lower Ordovician limestones.

These fensters lie about forty miles northeast of the well known fensters of Pulaski and Montgomery counties, Virginia, and represent the northernmost known occurrence of this type of structure in Virginia.

EVIDENCE OF BLOCK FAULTING ON THE COAST OF SOUTHWESTERN GREENLAND

BY R. L. BELKNAP[1]

(*Abstract*)

The profile from the coast inland across the Holstensborg district of Greenland presents several distinct sections similar to certain profiles of the better known Norwegian coast. Offshore the completely submerged banks are followed by a reef and skerry section which is in turn followed by a high, rugged coastal section, and this in turn by a lower hinterland zone which is overriden along its eastern margin by the inland ice. While fractures have received considerable attention, earlier investigators have given the impression that there has been little or no faulting in the area.

The author's field studies, carried on during the summers of 1926, 1927, and 1928, have led to the following conclusions: The fluctuations in level have been frequent and of considerable magnitude. They have been accompanied or followed by faulting. This faulting, especially of the block type, explains more easily than the theory of marine erosion the terraced condition of the coast. The same orographic blocks found along the coast of the Holstensborg district appear farther south along the coast of the Sukkertoppen, Godthaab, and Frederikshaab districts.

[1] Introduced by W. H. Hobbs.

NATURE AND ORIGIN OF THE HORST AND GRABEN STRUCTURE OF SOUTHERN OREGON

BY RICHARD E. FULLER AND AARON C. WATERS [1]

(*Abstract*)

In southern Oregon east of the Cascade Mountains a varied series of Tertiary lavas is cut by the northern continuation of the Basin Range faults, giving rise principally to relatively undissected horst and graben structure rather than to titled fault-block mountains. Of the five major fault depressions which lie in the Lake County and Harney County portion of this region, Alvord Valley, Guano Valley, and Warner Valley are true grabens throughout at least a large part of their length. Catlow Valley occupies a fault basin bounded mainly by curving rather than linear fault-scarps. The composite depression in which Summer Lake, Chewaucan Marsh, and Goose Lake lie is of more complex type.

Field studies by the writers in the Steens Mountain district do not bear out the recently published conclusion of Warren D. Smith that this mountain and the adjacent Alvord graben owe their origin to thrust-faulting, but, on the contrary, indicate that the faulting was accompanied by extension of the surface area. That the deformation was not compressional is indicated by definite normal faulting, curving and zigzag faults, step faults, circular fault-basins, volcanic activity parallel to the faults, absence of folds, thrust-faults, or other pressure effects, and by the even distribution of faults, instead of their local concentration in zones of initial failure.

Discussion

WARREN D. SMITH: Through the courtesy of Mr. Richard E. Fuller and Mr. Aaron C. Waters, I am able to present, at the time of the reading of their paper, an answer to some of their criticisms of my own paper on the same region, Steens Mountain. These investigators have taken exception to my findings under two main topics: first, the stratigraphy, and, second, the structure of that region.

In the first place, I should like to point out that the stratigraphic table in my paper is labeled "*tentative*," which clearly indicates that the material presented therein is provisional and open to question. This table was put out as a feeler, which would help crystallize what we know and what we might hope to find out about the subject, and was not meant to be considered final. Tables of this kind are very useful, as they help clear up just such matters as we are discussing. If we wait until we have all possible data about a region or problem, we might never get anything done. Under the circumstances, I am quite willing to take criticism if it leads to the final true statement of the facts.

The writers draw attention to the fact that I have placed the Trout Creek beds in the Lower Miocene. I should have, of course, given my reason for so doing, and in a later paper I have a footnote indicating that this is based on a previous communication from Dr. Chester Stock, of the California Institute of Technology. Although I am not familiar with all of the work that

[1] Introduced by Chester R. Longwell.

Dr. Stock has done in that region, and particularly on the Trout Creek beds, I believe he has found sufficient evidence which obliges him to question the earlier age assignment by F. H. Knowlton.

As for the placing of the Steens Mountain lavas in the Miocene and correlation with the Columbia River lavas, it was very distinctly brought out in my article that without paleontologic evidence this correlation would have to be provisional.

Concerning the Pliocene of the table, I think these authors have a very valid criticism. Certainly some of the basalt dikes do pass into the overlying lava flow as feeders, and therefore should be of the same age as the flows which they feed, and are, therefore, presumably of Miocene age. I believe, however, without having the evidence, that some of these dikes are of later date, feeding later flows which are not found on Steens Mountain at the present time.

The point about the two profiles of Abert and Steens Mountain is well taken. This was an error in draftsmanship which was overlooked by me. There should be a break between the two.

As for the structure, I am not surprised that there should be disagreement with me, and I am open-minded enough to accept any evidence which they may have found as to the existence of normal faulting on a large scale on the east side of Steens Mountain. They speak of frequent instances of slickensided surfaces. Without having seen any of these myself, I would be inclined to ask the question whether or not these could be formed as a result of landslides. Since I have not studied the mountain in as great detail as have these gentlemen, I would by no means refuse to accept their statements concerning the existence of normal faulting in that region. I can see how we might have normal faulting and yet the main structural feature, that of thrust-faulting, concealed beneath the talus of the fault-scarp. My main objection to the older notion concerning the formation of these grabens is on the grounds of the mechanics of the problem. I think that very few geologists have had sufficient training in mechanics to enable them to solve a problem of this kind. Certainly, I felt my own equipment in this direction to be lacking, and for that reason I put the problem to two tests. First, I consulted the best authority in mechanics available to me, Prof. E. H. McAlister, of the University of Oregon, who stated very definitely that, on theoretical grounds, to explain a structure of this kind through tension alone was mechanically unsound. And next I consulted what little experimental data there is available and found that Professor Jaggar had duplicated in the laboratory practically this same structure by means of compression. Again I invite attention to figure 143 in Daly's "Our mobile earth." Now if these experiments were not conducted properly and the professor of mechanics is in error in his statement, then, of course, I would be forced to accept some other explanation.

The undersigned has not attempted to find a more spectacular method of solving the problem, but he has made a sincere attempt to bring whatever facts we may have to bear on it. He has not asserted for a moment that he has all the facts, and if the writers of the present paper are able to prove, from more conclusive data, that my ideas as to the structure of this region are wrong, I shall be only too glad to change my position. I am not interested

so much in proving my own theories as I am in arriving at the truth, and this, of course, is the only thing of importance.

That the undersigned is not altogether wild in his interpretations of some of these structures in eastern Oregon is attested by the fact that a reexamination of apparently similar structures, namely, the great Rift Valley of Africa, and the Dead Sea trough in Palestine, the former by Wayland and the latter by Willis, has called for a more critical scrutiny of the problem than was given to it by some of the earlier investigators. I do not mean to say by this that what has occurred in East Africa and Palestine necessarily proves me right in eastern Oregon; it merely indicates the possibility of another interpretation than the older one being correct. Dr. Bailey Willis's recent paper on the subject of the Dead Sea trough is most illuminating and suggestive in connection with this problem in Oregon.

GLACIER STAGNATION AND THE DISSIPATION OF THE LAST ICE-SHEET

BY RICHARD FOSTER FLINT[1]

(*Abstract*)

The areal studies of glacial phenomena made in the past in New England and adjacent regions have been based on the assumption that the last ice-sheet retreated from south to north, maintaining throughout its retreat a well defined front like that of a modern valley glacier. The object of the present argument is to show that this was not the case, but that instead the ice-sheet lost its motion while at its maximum extent, and that therefore it rotted away *in situ*, the ice near its southern periphery disappearing last of all. The case is first presented theoretically. Normal retreat (of live ice with a well defined southern front) is assumed, and the consequences in terms of land forms are deduced. Stagnation *in situ* of the same initial mass is then assumed and the consequences deduced. When the two sets of deductions are compared with the facts yielded by a field survey of Connecticut, and by examination of other regions, normal retreat is controverted and stagnation shown actually to have taken place. The field criteria for stagnation are discussed in detail. The field evidence indicates that errors have been made in the correlation of the varved clays of the Connecticut Valley and in the chronology derived from them. Apparently the evidence further indicates that postglacial uplift has not affected the Connecticut-Long Island region. Stagnation probably affected nearly all of New England, New Jersey, and eastern New York. Also, there is evidence that the ice behaved similarly in certain places much farther west. The stagnation is believed to have been caused chiefly by the presence of major topographic barriers hindering ice movement.

Brief remarks were made by Messrs. J. L. Rich, George H. Chadwick, George D. Hubbard, Kirtley F. Mather, James H. Lees, Alfred C. Lane, Ernst Antevs, with reply by the author.

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[1] Introduced by Adolph Knopf.

PENNSYLVANIAN OUTLIER AT SAINT LOUIS, MISSOURI, AND ITS CORRELATIONS

BY J. BROOKES KNIGHT [1]

(*Abstract*)

A columnar section of the Saint Louis-Pennsylvanian outlier is presented. It is shown that the beds are referable to the uppermost Cherokee, the Henrietta and the lower part of the Pleasanton formations of the standard Missouri section. It is shown that the Fort Scott member of the Henrietta formation, with its upper and lower limestones and its shaly and generally carbonaceous middle division, is the equivalent of the Belleville coal (generally correlated with number 6 of southern Illinois) with its cap rock and the limestone that closely underlies it in the neighboring Illinois coal fields. It is also shown that the Bevier coal of the Cherokee is the equivalent of the coal formerly mined in Calhoun County, Illinois, which coal is also represented in the Illinois bluffs of the Mississippi south of Belleville. This is coal number I-A of the Worthen reports, possibly to be correlated with number 2 of the present Illinois section.

MISSISSIPPIAN AND PENNSYLVANIAN STRATIGRAPHY OF TRANS-PECOS TEXAS [2]

BY ROBERT E. KING [3]

(*Abstract*)

Mississippian and Pennsylvanian rocks occur in trans-Pecos Texas principally in the folds of the Marathon basin and in the Franklin and Hueco Mountains. They are also present in a small area at the base of the Sierra Diablo and in the Solitario uplift. Rocks in other areas of this region which were mapped originally as Pennsylvanian have since proved to be Permian. In the Marathon basin there are four divisions: the Tesnus shale and sandstone, the Dimple limestone, the Haymond shale and sandstone, and the Gaptank shale containing layers of limestone and conglomerate. The first three are practically unfossiliferous. The Gaptank contains several faunas. Those from the lower part enable correlation with the lower Canyon, while fusulinids from the higher beds are of the same species as those of the middle Cisco. In the northwestern part of the Marathon basin, below the Dugout Creek overthrust, a prolific fauna of ammonoids was collected. In the Hueco Mountains the Helms formation, composed largely of sandy limestone and shale, overlies the Silurian Fusselman limestone. Only its upper part is fossiliferous; the fossils are of Chester age. The lower part of the formation may be lower Mississippian. Above are 75 to 150 feet of limestone, chert, and siliceous shale, which contain a Bend or Morrow fauna. There is an erosional unconformity between these beds and the overlying limestone containing a Strawn fauna. The beds of Strawn age comprise a massive limestone

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[1] Introduced by C. O. Dunbar.

[2] Published by permission of the Bureau of Economic Geology, University of Texas.

[3] Introduced by Charles Schuchert.

bearing great masses of *Chaetetes*. The equivalent of the Canyon and lower Cisco is also mainly limestone, which contains a red conglomerate member near the top. A considerable structural unconformity separates the Pennsylvanian from the Permian. In the Franklin Mountains the Pennsylvanian probably is mostly Bend and Strawn in age; beds of upper Devonian and Mississippian age may also be present there. In the Sierra Diablo there is 150 feet of limestone of Strawn age. Since the Helms thickens from north to south, an equivalent of it would be expected in the Marathon Basin; this is probably the Tesnus. The Dimple and Haymond seem to correspond with the beds of Bend and Strawn age respectively in the Hueco Mountains.

AGAWA IRON FORMATION OF NORTHEASTERN MINNESOTA

BY J. T. STARK [1]

(*Abstract*)

In the vicinity of Kekequabic Lake, northeastern Minnesota, the Agawa iron-bearing formation (Lower Huronian) exhibits evidence of mechanical concentration as the origin of the iron lenses. Field relations and microscopic study reveal the definitely clastic nature of the iron bands and the enclosing andesitic tuffs which were deposited in the Huronian sea of this area shortly after the formation of the Ogishke conglomerate. No evidence of chemically precipitated silica or jasper was found, the lighter colored bands of the iron formation being the result of weathering of the tuffaceous beds. Considering the Kekequabic area only, it is believed that gravity, flotation, and subsequent leaching may have been the only concentrating agents. This conclusion is based on the fragmental character of the iron bands; the iron-rich particles of the andesite in the enclosing tuffs; the progressive gradations from tuffs to lenses rich in iron, and the inverse relation between amounts of horneblende and feldspar to the richness of the iron.

Read by title in the absence of the author.

CHESAPEAKE MIOCENE BASIN OF SEDIMENTATION AS EXPRESSED IN THE NEW GEOLOGIC MAP OF VIRGINIA

BY W. C. MANSFIELD [2]

(*Abstract*)

The formations comprising the Chesapeake Miocene group in Virginia and Maryland are indicated in two generalized sections, the development of the formations in Virginia being briefly discussed.

The western limit of each formation is indicated on a combined map of Maryland, Virginia, and North Carolina.

The distribution of the formations in Virginia seems to show that the Saint Marys formation, at the south, overlaps the Choptank and Calvert formations, and that the Yorktown formation transgressed westward over all older formations of the Coastal Plain and laps over a few miles onto the crystalline rocks, which underlie the eastern border of the Piedmont Plateau.

[1] Introduced by U. S. Grant.
[2] Introduced by L. W. Stephenson.

A somewhat hypothetical section is drawn from Crisfield, Maryland, to Jacksonville, North Carolina, showing that the downwarping, which initiated the deposition of the Chesapeake group, began at the north and progressed southward to the Carolinas. The section becomes thinner at the south by pinching out of formations older than the Yorktown.

A slide of a section below Yorktown and another of the upper sections of well borings in the Norfolk Quadrangle are shown to indicate a suggestion of possible structure.

Slides are shown of a few exposures of the Chesapeake Miocene deposits and of a few characteristic fossils occurring in the different formations.

The new map of the Chesapeake group of Virginia, as compared with the former map of the State, based on the work of Clark and Miller on the Coastal Plain province of Virginia, published in Bulletin 4, Virginia Geological Survey, 1912, shows, in general:

Less areal distribution of the Calvert formation;

The presence of the Choptank formation;

Less extensive areal distribution of the Saint Marys formation south of the James River;

Much more extensive areal distribution of the Yorktown formation.

DUGOUT CREEK OVERTHRUST OF WEST TEXAS[1]

BY PHILIP R. KING[2]

(*Abstract*)

The Dugout Creek overthrust was produced by the Caballos disturbance, which closed the Pennsylvanian in West Texas. It outcrops along Dugout Creek, west of the town of Marathon, in the northwest part of the Marathon Basin. This is a domelike post-Cretaceous uplift in which strongly folded Paleozoic rocks are laid bare by erosion. The trend of the Paleozoic folds is northeast to southwest and they are generally overturned toward the northwest. In the Glass Mountains, which flank the basin on the north, Permian strata rest unconformably on these folds and are in turn unconformably overlain by the Comanche series.

The Dugout Creek overthrust is a part of the old folded system. Ordovician and Devonian (?) cherts, limestones, and novaculites form the overthrust block, and shales, sandstones, and thin limestone layers of the Gaptank (upper Pennsylvanian) form the overridden block. The intervening earlier Pennsylvanian Tesnus, Dimple, and Haymond formations are cut out by the faulting. The plane of the thrust is nearly flat, as traced along its frayed, dissected margin, where well exposed, 7 miles west of Marathon. Outliers of the overthrust sheet, mostly of novaculite, are found resting on the Pennsylvanian as much as 4 miles from the main front of the fault, giving a known displacement of 5½ miles.

The brittle rocks of the overriding mass are broken into an imbricate structure by secondary thrust-faults directed upward at a steeper angle than the main thrust. The incompetent beds beneath the thrust have been minutely

[1] Published by permission of the Bureau of Economic Geology, University of Texas.

[2] Introduced by C. R. Longwell.

deformed by small folds and thrusts. At one locality a limestone bed is in this manner repeated twelve times in the course of one-quarter of a mile. There is no metamorphism of the beds involved. The soft shales are somewhat indurated, but are still shales. Thrust breccia is developed locally, but is of small thickness, consisting of angular chert and novaculite fragments in a siliceous matrix.

The age of the thrust can be determined with somewhat more exactitude than most of such structures. The youngest rocks involved are found where a limestone layer directly beneath the thrust, 7 miles west of Marathon, bears a new ammonite fauna more advanced than that of the lower Cisco, and thus of late Pennsylvanian age. The oldest beds after the movement are of Wolfcamp age; ammonites were collected in them at the top of 400 feet of coarse boulder conglomerate, which rests in one place on novaculite of the overthrust block and in another on steep-dipping or even overturned Gaptank. These ammonites include *Perrinites cumminsi* (?), which suggests equivalency of these beds with the upper Wichita. Elsewhere older Permian beds come in conformably beneath, and therefore the thrusting occurred near the close of the Pennsylvanian.

STRUCTURAL GEOLOGY OF THE EASTERN PART OF THE BOSTON BASIN

BY MARLAND BILLINGS[1]

(*Abstract*)

The Boston Basin is a lowland portion of the New England physiographic province. It is approximately 24 miles long in an east-west direction and 15 miles wide in a north-south direction. The stratigraphic column includes a basement complex of igneous and metamorphic rocks and a stratified series of Carboniferous volcanics, conglomerate, tillite, argillite, and quartzite. The present paper sets forth an interpretation of the structure that differs considerably from preceding ideas. The structures in general strike east-west and the intensity of the folding decreases from south to north. In the southern third of the basin steep dips and overthrusts prevail, but in the northern two-thirds broad, open folds are characteristic. The southern third of the basin is a typical shingle-block structure, and each of five anticlines has been broken along its northern limb and thrust up over the anticline to the north. The strata and faults of these blocks dip steeply to the south. It is believed that they originally developed with a relatively low dip to the south and were greatly steepened by an underthrust from the south in the closing stages of the orogeny. Another fact which demonstrates that the pressure was from the south is that the heights to which the anticlines have been uplifted decreases from south to north.

Four vertical north-south tear-faults cut the basin into five segments and in each case, with one possible exception, the segment west of a particular tear-fault has migrated northward relative to the segment east of the same fault. The most westerly segment has migrated nearly two miles farther north than one of the eastern segments. The movements along these faults are related to the Narragansett tectonic arc of the northern Appalachians.

[1] Introduced by Kirk Bryan.

CHANGES OF BASELEVEL INDICATED BY CAVES IN KENTUCKY AND BERMUDA

BY A. C. SWINNERTON [1]

(*Abstract*)

The most important of the factors influencing the development of systems of caverns in soluble rocks in humid regions is the movement of the ground water. Ground water is not a sufficiently effective solvent to produce caverns merely by occupying the pores and joints of what are termed soluble rocks. Quantities of water must flow along the joints and soak into the adjoining pores in order to remove significant amounts of rock.

In the simplest case precipitation passes more or less directly downward through the openings in the rock to the water table and then moves laterally in the fluctuating top of the water table into the surface drainage channels. Insignificant caves may occur both above and below the water table as temporary phases of the adjustment of subsurface flow to the level of the surface streams, but it does not seem possible that continuous systems of caves can develop below the zone of actively circulating ground water—that is, below the water table. The water table is dependent on the level of the surface streams; these in turn depend on the regional baselevel.

In view of the foregoing, it seems reasonable to formulate the hypothesis that systems of caves can not develop beneath regional baselevel; that the lowest levels of systems of caves approximate the baselevel of the region at the time the caverns were excavated.

In the light of this hypothesis, the lowest levels of Mammoth, New Entrance, and Great Onyx caves, Kentucky, represent the active zone of cave development approximately at the altitude of the Green River. So-called cave levels may be found at many altitudes, but the continuous system of caverns at approximately 200 feet above the level of the river is so strongly marked that it may be regarded as indicating an intermediate erosional stage in the physiographic history of the region.

In Bermuda various data point to a comparatively recent moderate submergence of the islands. The caves in Bermuda extend below sealevel and, in themselves, may be regarded as indicative of at least one stage of greater elevation in the history of the islands. From measurements of the depth of water in the caves, allowing for fallen roof fragments, it seems evident that the islands have been submerged between 50 and 60 feet. The relation between caves and baselevel permits a quantitative approach to the problem of change of level.

Brief remarks were made by Messrs. J. J. Galloway and R. W. Sayles.

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[1] Introduced by R. W. Sayles.

PLEISTOCENE LAKES AND LAKE DEPOSITS IN NORTHWESTERN QUEBEC

BY JAMES E. GILL [1]

(*Abstract*)

Beaches formed by glacial lakes are preserved in many parts of Temiskaming County, Quebec. The highest observed now stands at 1,200 feet above sealevel. Successions of beaches show that the lake waters fell by short stages, 5 to 45 feet at a time, down to an elevation of 1,000 feet. The deposition of clays, silts, and sands and the reasons for their present distribution are discussed.

FURTHER EVIDENCE OF KEYSTONE FAULTS

BY IRVING B. CROSBY [2]

(*Abstract*)

A new example of keystone fault which illustrates the special features of this peculiar type of faulting better than any hitherto seen was recently found near the Sainte Maurice River, some 30 miles north of La Tuque, Quebec.

This type of faulting was first described in an article entitled "Keystone Faults," by W. O. Crosby and Irving B. Crosby, and was published in the Proceedings of the Geological Society of America, volume 36, pages 623 to 640, December, 1925.

This new example of the keystone fault clearly answers some of the criticisms which have been brought against the theory. Downward displacement is evident, the converging joints can be plainly seen, and the intervening block has dropped about 25 feet. The absence of glacial boulders and debris in the chasm indicates that it is postglacial.

SCIENTIFIC BASIS OF ANCIENT HINDU COSMOGONY

BY V. R. KOKATNUR [3]

(*Abstract*)

In view of the recently reported discovery of the center of the universe by Professor Shapley, the knowledge of such a center in ancient Hindu cosmogony should be of timely interest.

The substance of the Hindu theory of cosmogony is as follows:

In the beginning, the primordial substance composed of material known as "Akasha" was in perfect equilibrium. This equilibrium was disturbed by a force known as "Adhogamana," or attraction. Affected by attraction, the particles of the primordial substance coagulated to a cloudlike mass and began to rotate, and, due to the eccentric position of attraction, this rotatory motion became elliptical.

The area of disturbance was also egg-shaped and was known as "Brahmanda." The center of disturbance was known as "Adha" or "Brahma" and is the center of the universe.

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[1] Introduced by Harold L. Alling.
[2] Introduced by A. C. Lane.
[3] Introduced by Charles P. Berkey.

Due to this rotation, numberless portions broke off and were known as "Adtyas," or suns, which were composed of "Vayu," or vaporous material. The suns broke off into "Grihas," or planets, and planets into "Chandras," or moons.

As the earth's revolution around the sun gave rise to four seasons, the sun's revolution round the center of the universe gave rise to "Yugas," or ages.

"Pralayas," or deluges, were like tides produced by the conjoint attraction of the center of the universe, the sun and the moon on the earth.

MODIFICATION OF THE THEORY OF MAGMATIC CYCLES

BY GERALD R. MACCARTHY [1]

(*Abstract*)

According to the Joly-Holmes theory of magmatic cycles, the heat produced by radioactivity and trapped beneath the continental plates causes fusion of the subcontinental basalts to such an extent that a partial foundering of the lands takes place and the continents, at a lower level, are invaded by epeiric seas.

The continents could not sink into the fusing substratum, however, without displacing it. This displacement and consequent escape of the basalts from beneath the continents must obviously be coincident with the epochs of transgressing seas. For such a sequence of events to take place the magmas must escape as rapidly as formed, and no periodic crises of diastrophism could be produced.

If we assume that the basalts do not escape when melted, but remain beneath the continents, the continental plates would rise, buoyed up by the additional layer of relatively light material (the fused basalts) thus added to their lower surfaces. Erosion of the landmasses would accumulate sediments around their edges and produce marginal subsidence, so that the continental plates would come to resemble shallow, inverted saucers. If these marginal areas were depressed sufficiently they might reach such a depth that fusion would result, and the granitic magmas thus formed would migrate upward and inwardly, collecting in the central portion of the area above the denser basaltic magmas. Meanwhile, the depressed margins of the plates would serve as a barrier to lateral outflow of magma. Central rise and erosion, coupled with peripheral sedimentation and subsidence, would continue until the margins were so far depressed and weakened that the basaltic magmas, breaking through them, could escape laterally.

The central portion of the area, its support removed by this outflow of magma, would sink, subjecting the marginal prisms of sediments to lateral pressure with the development of typical mountain structure. Any intrusive activity of the granitic magmas which had collected in the more central portions of the region would tend to promote this lateral pressure by a shouldering action. At the conclusion of the cycle the landmasses involved would again lie at a relative level and would be bordered by a more or less complete belt of crushed sediments.

Brief remarks were made by Prof. Alfred C. Lane.

[1] Introduced by George R. Mansfield.

ECOLOGIC BASES FOR STRATIGRAPHIC DIVISIONS

BY CARROLL LANE AND MILDRED ADAMS FENTON [1]

(*Abstract*)

In many cases stratigraphic divisions of zonal or subzonal order must be based primarily on the vertical range of a few selected organisms, generally termed index fossils. The areal range of these organisms is made the basis for correlation and mapping of the geologic units which they characterize.

Often, however, collections are available which represent in detail the faunal content of limited stratigraphic divisions, especially those to which we have applied the term zonule.[2] By identifying these collections, tabulating them, and determining the probable life habits of as many species as possible, a fairly accurate picture of faunal associations may be secured. Data on the environment is furnished by the sediments and by many peculiarities (small or large size, distortion, disposal, etcetera) of the specimens themselves; assembled and interpreted, they indicate the ecology of the formation. It is these data which seem most reliable in the determination of zonules and subzones, while they have at least secondary significance in the delimination of zones and stages. In correlation, they bridge or explain some of the gaps in the distribution of index species; when assembled for numerous formations, they will be of value to the paleogeographer.

Read by title.

GRAVITATIONAL THEORY OF OROGENY RECONSIDERED

BY M. G. CHENEY [3]

(*Abstract*)

The outstanding geological characteristics of folded mountain areas are crustal failure and a rock column of abnormally light density (high elevations in approximate balance isostatically). Crustal weakening and change of average density of rock column seem unavoidable consequences of extensive erosional uplifts and deep sedimentary basins. The restricted occurrence of folded mountains to areas of former deep basins appears significant. It is believed that the lateral compressive movement which crushes the weakened basin is more likely due to adjustment of unbalanced conditions between complementary basin and erosion areas than to drifting of entire continents or subsidence of ocean floors.

NEW INTERPRETATION OF PERMO-CARBONIFEROUS VARVES AT SQUANTUM

BY ROBERT W. SAYLES

(*Abstract*)

Ever since De Geer, in 1878, and Emerson, Taylor, Berkey, and others, later on, have written on seasonal banding in the glacial clays, the varve,

[1] Introduced by N. M. Fenneman.
[2] American Midland Naturalist, vol. 11, 1928, p. 20.
[3] Introduced by Charles P. Berkey.

named by De Geer, has been considered to mean a summer season of warmth, indicated by alternating thin layers of fine sand, silt, and clay layers, and a winter season cold enough to freeze up the waters coming from the glaciers, so that nothing but the settling of the clays on the floor of the water body in front of the ice-sheet took place. The two components together would indicate a full year's deposition.

In 1915 the writer found that the glacial slates lying on the Squantum tillite had characters which indicated that seasonal deposition took place in Permo-Carboniferous times as well as in the Pleistocene period. In the slate well above the tillite the features of the bedding resembled exactly those of the interglacial clays at Grantsburg described by Berkey in 1905.* The presence of a sandy layer in many of the specimens was the only difference, and this was explained by the writer as the result of great heat or of wind action at the beginning of cyclonic control in the fall.

In 1925 the writer found in a quarry on Foster Street, Brighton, Massachusetts, thick varves which showed conclusively that the winter components, as indicated by the alternations of coarse and fine layers, was a season of greater warmth than the Pleistocene winter. Also, that the summer season was indicated by a layer of sand followed, usually higher up in the slate, by a layer of fine material of varying thickness, which would indicate the beginning of the cold season. The deposition must have been rather rapid. Then followed the winter, with currents of water coming from the ice always strong enough to make finely stratified deposits in the basin of deposition not too far from the ice.

Wallace and the writer both published in 1927 accounts of the broken nature of the winter components, Wallace writing about the slate with the Cobalt tillite and the writer about the Squantum slate. The sandy layer was not mentioned as occurring in the Cobalt slate, but the writer has a specimen of that slate in which the sandy member shows regularly. Wallace recognized the fact that the winters of the Cobalt slate must have been warmer than our Pleistocene winters. From Australia a specimen of slate associated with the Cambrian tillite shows also broken winter components. From Uganda, equatorial Africa, Precambrian slate shows like characters. Photos of ancient glacial slates from other parts of the world show what appear to be broken winter components, but photos can not be trusted for texture.

The interpretation of seasons from varve structure can not yet be used safely, but with the study of varve slates from all sources possible we may be able to arrive at definite conclusions regarding the nature of Precambrian, Cambrian, and Permo-Carboniferous glacial climates, and such a study might possibly throw light on continental drift.

Read by title.

At this point the session adjourned, at 6 o'clock.

Session of Thursday, December 27

One of the outstanding features of the program was a symposium on the Centenary of the Glacial Theory, organized by Prof. Henry Fairfield

Osborn, who acted as chairman of the meeting. This was held at 2 o'clock, in the Auditorium of the American Museum of Natural History. The new world maps, especially prepared for this meeting through the cooperation of the American Geographical Society and the Carnegie Institution of Washington, were presented, and the following papers were read:

SYMPOSIUM ON THE CENTENARY OF THE GLACIAL THEORY

The following six papers were devoted to this subject:

TITLES AND ABSTRACTS OF PAPERS

INFLUENCE OF THE GLACIAL AGE ON THE EVOLUTION OF MAN[1]

BY HENRY FAIRFIELD OSBORN

(*Abstract*)

Theory, experience, and observation conspire to demonstrate that in the evolution of no other organism is the struggle for existence more important than in man. While many anthropologists still adhere to the Darwinian hypothesis, that man branched off from some member of the anthropoid ape family living in a warm, tropical, and forested region, I have been led to abandon this hypothesis and substitute an hypothesis of quite a different order, namely, that man branched off from the anthropoid stem during the period of the first onset of dryer and even semiarid conditions in certain of the plateau regions of the earth. It was this onset which rapidly exterminated those earlier types of mammals adapted to more luxuriant vegetation and to warmer climes and introduced a hardy type of mammals of the plateaus and plains. Theoretically it is probable that man, as a pro-biped, with free use of his arms and hands, branched off at this time.

When, however, the first actual evidence of man is discovered, in closing Pliocene time, the climatic and environmental conditions of life on the fourtieth parallel are mild and easy and man shows, accordingly, an extremely prolonged period of partly arrested development, owing to the relaxation of the struggle for existence. The first three glacial epochs pass away while there are no very marked or profound changes in the mammalian life of western Europe nor in the advance of man himself. The fourth glacial epoch changes all this and puts the older Neanderthal races to a very severe test, culminating in the arrival of new higher races, as we believe, from the central plateau regions of Asia. This is a second great application of the principle of the struggle for existence to the evolution of man. Throughout this long period, from the close of the Pliocene until the present day, it may be said that we, perhaps, are chiefly dependent on glacial phenomena not only for the chronology of man, but for an adequate theory for the mental and spiritual evolution of man.

[1] Abstract of paper presented at the symposium on the centenary of the glacial theory.

The following outstanding points, taken from a paper written by Dr. Reeds and myself in 1922, will summarize this chronology and influence of the Ice Age:

"A matter of supreme human interest in anthropology at the present time is the appearance of man in the successive stages of the geologic history of Eurasia and of Africa. The recent coordinations of Depéret have set a new basis of time division for the whole Quaternary. The researches of De Geer establish the past fifteen millennia. When combined, they support, with certain modifications, the pioneer work of Penck and Brückner. The historic bases of Pleistocene subdivision have been the following:

"1. *Astronomic:* as in the studies of Croll (Croll, 1875.1), Wallace (1880), and others.

"2. *Paleogeographic:* epirogenic movements—that is, continental elevation (marine regression) and subsidence (marine transgression).

"3. *Sealevel changes:* eustatic movements—that is, negative (marine regression); positive (marine transgression), Suess (1885.1), Schuchert (1901.1), de Lamothe (1899.1, 1901.1, 1911.1, 1916.1, 1918.1), Gignoux (1913.1), Daly (1920.1, .2), Depéret (1918-1921).

"4. *Paleometeorologic:* atmospheric (for example, Chamberlin, 1907) and climatic change, due to 1 and 2.

"5. *Glacial and interglacial phenomena*, Geikie (1894.1, 1914.1), Penck, and Brückner (1909.1), Leverett (1910.1) and others correlated with 1 to 6.

"6. *River terraces:* erosions and deposits, correlated with 1 to 3.

"7. *Other continental geologic deposits:* fluviatile sands, moraines, clay laminæ (for example, De Geer, 1910-1921), loess, correlated with 1 to 5.

"8. *Paleobotanic:* terrestrial and aquatic flora, correlated with 1 to 6.

"9. *Paleontologic: invertebrate* fauna in marine shorelines (Depéret), fluviatile and continental deposits, correlated with 1 to 7.

"10. *Paleontologic: vertebrate* fauna and migrations, terrestrial and fluviatile, correlated with 1 to 8.

"11. *Archeologic:* succession of human industries in stone and bone, correlated with 1 to 9.

"12. *Anthropologic:* evolution and migration of human races, correlated with 1 to 10."

Since this joint Osborn-Reeds paper of 1922 was prepared many very important discoveries have been made, all tending to carry back the human culture stages into earlier periods of geologic time. For example, the pre-Chellean is now assigned to the first interglacial stage, equivalent to the Aftonian of America. The Chellean accordingly moves down to the second interglacial stage, according to more recent observations of archeologists, in which Professor Penck concurs. This rearrangement was substantially shown in the tables prepared by Dr. N. C. Nelson, archeologist of the American Museum, and in the Osborn-Reeds chart of 1922 as modified by Professor Penck.

The archeological discovery of greatest importance, however, is that of the "rostrocarinate" and other well shaped flints found beneath the Upper Pliocene Red Crag of England. Undoubtedly of preglacial age, these compel us to thrust the evolution of tool-making man far back into Pliocene and

perhaps into Miocene time. Possibly of Upper Pliocene age also is the famous Piltdown man of Sussex, *Eoanthropus*, although the evidence is also capable of a Lower Pleistocene interpretation. In far-away Java the Trinil man, formerly regarded as Upper Pliocene, now appears to be of Middle Pleistocene age—an instance of retarded evolution. Finally, in Central Asia the pulse of the Glacial Age is felt in humid conditions which prevailed in the desert of Gobi between twenty-five and forty thousand years ago, favoring the rapid spread and multiplication of the dune-man race and culture, as discovered and described by Andrews, Nelson, and Berkey of the Central Asiatic Expedition.

In conclusion it may be said without exaggeration that our rapidly advancing knowledge of the anthropology of the Stone Age is largely due to the triumphant applications of the glacial theory of Charpentier and Agassiz, which is now celebrating its centenary.

WEATHER AND GLACIATION

BY CHESTER A. REEDS

Read by title in the absence of the author.

NEW MAPS OF PLEISTOCENE GLACIATIONS, NORTHERN HEMISPHERE

BY ERNST ANTEVS

(*Abstract*)

One of President H. F. Osborn's suggestions in connection with the symposium on the Centenary of the Glacial Theory was the preparation of maps showing the extent of Pleistocene glaciations, according to present knowledge. Such maps are much needed by anthropologists, botanists, and zoologists, as well as by geologists. For the realization of this idea President Osborn appointed a committee and obtained the support of the Carnegie Institution of Washington.

A series of wall maps were prepared for the meeting in scales varying from 1:10 million to 1:2.5 million. These maps show, so far as known, the extent of the probable five Pleistocene glaciations in the United States of America, of the glaciated area in Canada and Arctic North America, of the glaciated area and of the last glaciation in Europe, and of the glaciated area in Asia. The material has also been transferred on a new hemispherical map of the world.

SWINGING SEALEVEL OF THE ICE-AGE

BY REGINALD A. DALY

(*Abstract*)

A discussion of the position of sealevel: (*a*) on an ice-free earth; (*b*) in the late Neolithic time of Europe; (*c*) during the Glacial Period as ordinarily defined. The elastic and non-elastic effects of changing water-loads on the earth's body are considered in relation to the various strand-lines of the Pleistocene. Some of the geographical results of the last upward shift of sealevel are listed. Among them is the formation of the living coral reefs,

atolls, barriers, and fringes. Explanation of these reefs by assuming subsidence of their foundations is no longer necessary and, in addition, is not supported by the facts of observation.

CLIMATIC ZONES AND PERIODS OF GLACIATION

BY WILLIAM H. HOBBS

(*Abstract*)

The evidence is presented that the period in which we live is a very brief and most abnormal one in the earth's geological history, such as has occurred, so far as we know, but once before since the beginning of the Cambrian. Whereas the earth's climate is today sharply differentiated with respect to latitude, so that we distinguish between torrid, temperate, and frigid climatic zones, the evidence goes to show that, almost throughout since the beginning of the Paleozoic, uniformity of climate has extended from the equator almost, if not quite, to the poles, with subtropical humid conditions. The abnormal condition of sharp differentiation into climatic zones which was characteristic of the Permo-Carboniferous and the Pleistocene-Recent, appears to have been causally connected with widespread glaciation of the continential type.

The mechanism of the process by which the zonal property of climate is brought about and maintained is in part due to the fixed anticyclonic air circulation set up by the basal refrigeration of air over a domed surface of ice—the glacial anticyclone—and in part to the abyssal circulation of cold oceanic currents fed by ice-caps within high latitudes.

PLEISTOCENE GLACIATIONS OF THE NORTHERN HEMISPHERE

BY FRANK LEVERETT

(*Abstract*)

In an introductory statement the basis for considering this a centenary year in glacial geology is found in the beginning of glacial studies by Charpentier and Hugi in 1828. A brief outline is given of preceding investigations and interpretations of glacial phenomena back to 1695.

The distribution of Pleistocene ice-sheets and of mountain glaciation is briefly presented. The glaciated area was never completely covered at any one time, but is a composite of successive phases of ice extension. This is true of the area covered in each glacial stage as well as of that embraced in all the glacial stages.

The initial factors in the growth of ice-sheets are shown to involve altitude above the Ice Age snowline and a location in the belt of great storm frequency. As sequential factors, the ice-sheet controlled air currents and probably also caused sufficient lowering of snowline to bring in additional areas. The latter is thought to find illustration in the later glaciation of Scotland than that of Scandinavia, and a still later glaciation of Ireland, in the last glacial stage and probably also in earlier stages. In each glacial stage the ice appears to have started on the height of land in Norway and later to have covered the Baltic lowland until that became the axis of ice dispersion. In the area of the Laurentide ice-sheet of North America the elevated Labrador Peninsula and Height of Land south of Hudson Bay be-

came glaciated earlier than the district to the west and probably also earlier than that south of the Saint Lawrence Valley from New York eastward. This was the case in the Wisconsin glaciation, appears to have been also in the Illinoian, and is likely to have been in earlier glacial stages. The mode of development of Cordilleran glaciation in western North America is not well worked out, even for the last glacial stage, and very little is known as to the earlier ones. It was largely a confluence of mountain and piedmont glaciers. This seems also to have been the case with the glaciation in Scotland, Wales, and Ireland.

The first suggestion of an alternation of cold glacial and warm interglacial stages seems to have come from Oswald Heer's studies of an interglacial warm climate flora between glacial deposits in the Alps, first noted about 1844. This line of evidence has been found to be widespread, and warm climate plants occur at more than one horizon. The animal life also, as represented in fossils in deposits between drift sheets, indicates similar warm conditions. This evidence is now sufficiently full to make certain that there were considerable fluctuations in temperature over the glaciated areas, and that they were repeated not less than four times. Independent of the interglacial beds, repeated glaciations may be inferred from a comparison of the degree of weathering and erosion of drifts of different ages. It was on this basis that Ramsay, in 1854, recognized drifts of widely different age in Wales. Chamberlin and his associates have used weathering and erosion to a great extent in working out the series of drifts in the United States. The weathered surfaces of the older drifts, when buried beneath later drifts, are easily recognized, not only in natural exposures, but in material brought up in borings. The evidence is especially clear when the older drift carries a soil or gumbotil at its surface. This evidence was cited in reports by members of the Ohio Geological Survey about 1870, and a little later by N. H. Winchell in reports of the Minnesota Geological Survey, and by McGee in scientific journals. Winchell at this time made clear the presence of three drifts in Minnesota.

In Europe the occurrence of distinct glacial and interglacial stages has been based more largely on the fauna and flora of interglacial beds than in America. This is partly due to the neglect of this study in America, though the borders of the Baltic Sea seem to be an exceptionally fertile field for such study. In both Europe and America loess deposits are present between certain drift sheets, and serve to show a temperate and relatively dry climate between glacial stages.

There is at present much difference of opinion as to the number of glacial and interglacial stages by students in different fields as well as by students in the same field. This is due largely to the imperfect state of our knowledge. Evidence of four glacial stages has been found in the Alps and at least four in the United States, but there is some difference of opinion as to the occurrence of more than three glacial stages in northern Europe, though the balance of evidence seems to favor four stages.

In most of the glaciated mountain areas of Asia only two Pleistocene glacial stages have been recognized and in some of them but one stage. Whether this lesser complexity actually exists or is due to imperfect knowledge remains to be determined. Correlation of these Asiatic glaciations with the Alpine

series has been attempted by some authors, but the basis of correlation seems rather questionable.

It seems clear that a lowering of temperature rather than an increase in precipitation was the chief factor in bringing on the glacial stages. The cause for the lowering of temperature is a matter of wide difference of opinion.

At the conclusion of the symposium, the following two papers were given:

PRESENTATION OF THE NEW WORLD MAPS

BY CHESTER A. REEDS

In the absence of Doctor Reeds, the maps were presented by Professor Osborn.

APPLICATION OF THE NEW WORLD MAPS

BY HENRY FAIRFIELD OSBORN

Session of Friday, December 28

ADDRESS OF THE RETIRING VICE-PRESIDENT

Opportunity was presented Friday morning, at 10:30, for the presentation of the address of Charles Schuchert, retiring Vice-President of Section E. The address is published in full in this volume, under the title "Geological history of the Antillean region."

GEOLOGICAL HISTORY OF THE ANTILLEAN REGION

BY CHARLES SCHUCHERT

(*Abstract*)

Central America and the Antillean Islands, in their present form, are the result of long-continued geological processes, mainly mountain-making and uplift, along with downwarping and fracturing into the depths of the seas, plus much volcanic activity. This development is the result of the earth's restless interior forces, which upheave or submerge parts of the crust, while the atmosphere erodes the protuberant parts through rain, wind, and temperature, and the ocean waves wear into the lands. It is in the main the history of the last 180 million years—that is, of Cenozoic and Mesozoic times—back of which lie at least 300 million more years, the time of the Paleozoic era, the history of which is very obscure in the Antillean region.

What stands out most clearly is that there was no Gulf of Mexico 100 million years ago, and that this deep-water basin came with the Cretaceous, when the Gulf was at least three times as large as it is now. Then the area of the Gulf of Mexico, northern Central America, most of the Greater Antilles, all of eastern Mexico and all of the Gulf States from Texas north

to Illinois and east to Florida were submerged by this greater gulf of marine waters. This condition endured for some tens of millions of years, and then, in Miocene time, began the elevating movements that have continued intermittently to the present, bringing on the geography as we now know it.

When the flood was greatest Costa Rica and Panama had grown from the bottom of the Caribbean Sea through Vulcan's outpourings until they had piled up the land bridge uniting North and South America. Costa Rica, however, soon subsided, and the Caribbean again sent its Gulf Stream into the Pacific during another ten million years. Then came permanent closure through elevation, along with more volcanic activity. The Gulf of Mexico shortly afterward, geologically speaking, began spilling across the Tehuantepec region, and this new portal remained an open seaway into the Pacific for a few million years. Decided elevation then set in almost everywhere, and soon all was land again between Central America and Mexico, and the plants and animals have had dry land for intermigration between North and South America ever since.

When Costa Rica-Panama became dry land for the first time, at the eastern end of the Caribbean Sea there also began to rise from the depths of the Atlantic Ocean a long string of submarine volcanoes, and about 50 million years ago the northern half of them appeared as the Caribbee volcanic islands, many of which have ever since retained intermittently active volcanoes. The newest of these volcanoes are the southern Caribbees.

The present geography came into existence more than a million years ago, but during this short geological interval the islands grew somewhat larger when northern North America and Europe were deeply covered by ice, but shrunk to their present dimensions when these ice-sheets melted back into the ocean, thus returning the water that had been taken from it.

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PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY

PROCEEDINGS OF THE TWENTIETH ANNUAL MEETING OF THE PALEONTOLOGICAL SOCIETY, HELD AT NEW YORK CITY, DECEMBER 27-29, 1928.

R. S. BASSLER, *Secretary*

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[1] Introduced by R. S. Lull.

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Session of Thursday, December 27

The twentieth annual meeting of the Paleontological Society was called to order by President Foerste, at 9 a. m., in the School Service Building of the American Museum of Natural History. Previous to this, on Wednesday evening, at 8 o'clock, the members attended the address of the retiring President of the Geological Society of America, Dr. Bailey Willis, entitled "Continental genesis," and following this the complimentary smoker given to the affiliated societies by our New York hosts. The usual introductory business session was postponed until later, so that the reading of papers was taken up at once.

Presentation of Papers

A new determination of a frequently quoted Lower Paleozoic brachiopod formed the subject of the first paper, illustrated by lantern slides. Discussion by Messrs. Ulrich, Kay, and Bassler.

Rafinesquina incurvata (Shepard), a Cincinnatian brachiopod

by G. Marshall Kay

(*Abstract*)

Shepard, in 1838, described *Producta incurvata* from "near Navarino, at the head of Green Bay," Wisconsin. The northern part of the present city of Green Bay was the town of Navarino in 1838. "*Strophomena incurvata* (Shepard)" has been commonly listed in paleontologic synonymy as a Black River or lower Trenton brachiopod. No Black River or lower Trenton rocks outcrop in the city. A study of the type locality reveals that a species of *Rafinesquina* is common in the Cincinnatian shaly limestones on Ellis Creek, three miles east of the city of Green Bay. The species is of the genus *Rafinesquina*, not of *Strophomena*, and it seems identical with the form illustrated by Shepard as *Producta incurvata*.

Strophomena incurvata of authors, not of Shepard, a Black River and lower Trenton form, is thus a misidentification of *Rafinesquina incurvata* (Shepard), a Cincinnatian species.

The problem of reef formation around one of the larger Fiji Islands was the next subject; presented by the senior author and illustrated by lantern slides.

REEFS OF VITILEVU, FIJI

BY HARRY S. LADD AND J. EDWARD HOFFMEISTER

(*Abstract*)

In this paper the various types of reefs found near the shore of the large island of Vitilevu are described in detail and the problem of their origin and history is discussed.

A generalized section across the reef flats from the seaward edge shows: (1) a narrow, flattish, marginal zone, where living corals are sometimes accompanied by calcareous algæ, (2) a broader zone, where *Acropora* is the dominant coral, (3) a zone, where *Porites* replaces *Acropora*, and (4) a broad, rocky flat scored by echinoid borings or silted over with sand and other reef debris. Other zones of living corals occur in certain sections. In general there is a fair variety of living corals, but rarely do the colonies cover large areas of the reef.

In some ways the problem of reef formation is simplified if only small islands are studied, for they rarely exhibit evidence of a prolonged and complex geological history. However, recent investigations by the writers seem to indicate that the history of some of these small islands is neither so short nor so simple as was previously believed. Furthermore, the origin of the platforms upon which modern reefs are built may be intimately tied up with the early stages of an island's history. Any theory for the origin of a given reef demands a full knowledge of the history of the near-by landmass. The geology of Vitilevu has been worked out in some detail, and it is believed that no single theory of coral reef formation can explain all the reefs surrounding it.

In the case of Vitilevu modern reef organisms seem to form but a relatively thin veneer over the surface of pre-existing platforms. These platforms have been formed in various ways: by degredation, by aggradation, and by earth movements.

There was then given, with lantern-slide illustrations, an exposition of the color markings in a number of Pennsylvanian mollusca, forming the most extensive assemblage of species so marked ever found in Paleozoic rocks. Discussion by Messrs. Thomas and Foerste.

SOME PENNSYLVANIAN GASTROPODS AND A PELECYPOD SHOWING COLOR MARKINGS

BY J. BROOKES KNIGHT

(*Abstract*)

In the course of his work on the Pennsylvanian outlier at Saint Louis, Missouri, the writer has been fortunate to find about fifteen species of gastropods and one species of pelecypod showing color markings. These are discussed

briefly and figured with particular emphasis on the color patterns. Questions of taxonomy are postponed for future consideration.

A study of the stratigraphic distribution of Silurian brachiopods of Missouri then followed, presented by the author and illustrated by charts.

BRACHIOPODA OF CERTAIN SILURIAN HORIZONS OF SOUTHEASTERN MISSOURI

BY JOHN R. BALL

(*Abstract*)

Studies in the faunas of the Brassfield and Bainbridge limestones of southeastern Missouri have been in progress since 1923. As far as they have been studied, the two faunas have yielded slightly over 150 species, including 58 that are new and 27 that have not been named specifically. The Brachiopoda compose nearly one-third the total number of species. Sixteen species have been noted in the Brassfield and 41 species come from the Bainbridge. Of the total number, 28 are regarded as new, 4 have been compared, and 6 have not as yet received a specific name. The species are distributed among 36 genera, 13 families, and 3 orders. The Protremata include 34, the Telotremata 20, while species of *Orbiculoidea* and *Crania* are the only representatives of the Neotremata. Of the Protremata 13 of the species are *Strophomenids*, 11 of them occurring in the subfamily *Rafinesquinae*. The *Orthidae* are the next group, with 8 species included. In the Telotremata the *Rhynchonellidæ* and *Meristellidæ* each have 6 species, while the *Atrypidæ* and the *Rhynchospiridæ* have 3 and 2 respectively.

Of the 13 *Strophomenids*, 7 come from the Brassfield, but 1 of the 7 occurs also in the Bainbridge. In the 8 *Orthids*, 2 only are in the Brassfield. The 6 *Rhynchonellids* are confined to the Bainbridge, but in the *Meristellidæ* 2 of the 6 species are in the Brassfield. The 2 species of the *Rhynchospiridæ* are in the Bainbridge, while of the 3 *Atrypidæ* 2 are restricted to the Bainbridge.

In respect to correlation, *Triplecia ortoni* and *Orthis flabellites dinorthis* are 2 of 6 characteristic Brassfield species occurring in the Missouri extension of that formation. Of Bainbridge fossils, *Dictyonella gibbosa* and *Trematospira simplex*, as far as known to the writer, have been reported only from the Brownsport beds of Tennessee. Both species are represented sparingly in the Bainbridge, and with these, in greater abundance, are *Strophonella dixoni* and *S. tenuistriata*, also reported formerly only from the Brownsport. *Strophonella laxiplicata* sparingly and *Merista tennesseensis* in great abundance are in the Bainbridge. Both of these are characteristic of the Brownsport and have been found also by C. A. Reeds in the Hunton of Oklahoma. The Bainbridge fauna, as a whole, includes nine characteristic Brownsport fossils, and nine of this group are in the Brachiopoda.

Included in the groups that are represented by many new species are the *Rhynchonellids*, which, confined practically to one facies of the Bainbridge, fairly dominate the brachiopod assemblage.

The great size of some of the boulders of the Caney shale was next discussed, and it was shown in the remarks by Dr. Foerste and the

author, which followed, that such large boulders are not uncommon in certain European localities of present-day ice.

LARGE SIZE OF ICE-TRANSPORTED BOULDERS IN THE LOWER PENNSYLVANIAN OF OKLAHOMA

BY E. O. ULRICH

At this point, due to a maximum attendance of the members, President Foerste called for two items on the business program. The first of these was the report of the Service Committee, given by Chairman Howell.

REPORT OF THE SERVICE COMMITTEE FOR 1928

At the Cleveland meeting of the Society is was voted to authorize the President to appoint a chairman and four members of a standing committee, to be known as the Service Committee, which should function as a clearing house for paleontological information for members of the Society, especially for members desiring to learn where they might obtain copies of out-of-print papers and specimens of fossils which they might need, the chairman to hold office at the pleasure of the Council of the Society, and to submit a written report on the services rendered by the committee during the preceding year.

My first report is submitted herewith.

During the year the committee has distributed to the members of the Society two information bulletins. As the contents of these bulletins are presumably familiar to all the members, they need not be discussed here. The committee plans to issue one such bulletin each spring and fall.

The committee has had many requests for information from members of the Society during its first year of activity. It has been able to be of service in each instance. I believe that it has demonstrated that it is worth while and can render services to the Society which will fully justify its existence. It has aided members to obtain current and out-of-print papers, to get photographic copies of papers which could not be obtained by purchase, and to purchase needed fossils. It has found a place of publication for manuscripts written by members. It has supplied information regarding a wide variety of subjects of interest to paleontologists. As was expected, it has been turned to more often by members who are located away from the larger centers of paleontological activity than by those working in such centers.

The committee has received valuable information and assistance from various members of the Society, for which I take this opportunity to express its gratitude.

Some members of the Society have written to the committee, stating that they will be willing to supply collections of fossils at small cost to other members who may desire them. The names of these gentlemen, and of other persons, not members, who have fossils for sale or are willing to make collections as desired, will be furnished to any member who requests them. It has not seemed feasible to publish them in the information bulletins.

The committee will be glad to assist in bringing together paleontologists in search of positions and organizations in search of paleontologists. Attention will be called to this fact again in the early spring, when young men about to receive their doctorates will be seeking openings.

Respectfully submitted,

B. F. HOWELL,
Chairman.

The third and final report on the marking of type specimens was then given by the chairman of the committee appointed for the study of this subject. After discussion by various members of this and the previous report, it was voted that both be adopted and printed in the proceedings and the thanks of the Society be extended to the committee for their valued services. It was further voted that the chairman of the committee be requested to prepare a chart and a set of definitions of type specimens to be included with the report.

THIRD REPORT OF SPECIAL COMMITTEE ON MARKING OF TYPE SPECIMENS

At the last annual meeting of the Society it was voted to authorize the President to reappoint this committee for one year, and to instruct it to proceed with its investigations and make at the next annual meeting recommendations regarding the best method or methods of marking type specimens of fossils in the museums of North America.

As the committee attempted to formulate recommendations it found itself faced with two questions:

1. What different kinds of type specimens should be indicated by different distinguishing marks?
2. What kinds of marks should be used?

In attempting to answer the first question, the committee divided all type specimens into four groups:

1. Basic types—that is, holotypes, cotypes (or syntypes), paratypes, lectotypes, and neotypes.
2. Supplementary types—that is, pleisotypes (or hypotypes), heautotypes, and allotypes.
3. Unessential published types—that is, figured specimens and cited specimens—specimens to which reference is made in a published book or paper, but which add nothing to our knowledge of the form of a species.
4. Unessential unpublished types—that is, topotypes, metatypes, homeotypes, and ideotypes.

Plastotypes and other reproductions of original types are merely replicas of the above types and do not require separate classification here.

The first two of these groups may be grouped together as essential types; the last two may be grouped together as unessential types.

As the committee knows of no simple name that has already been suggested for the types of group three, the unessential published types (those which have been figured or cited in the literature), it here proposes the new name, onomatype, meaning cited, quoted, or named type, for types of

this group which are cited, and the new name, morphotype, for figured specimens (the more appropriate name, graphotype, being preoccupied).

The committee proposes no new simple name except "unpublished types" for the types of group four.

In attempting to find the best answer to the second question the committee has felt that it must begin with the assumption that any feasible plan for marking type specimens must involve the recognition of these four fundamental groups and the use of symbols for them which can at a glance be told apart and recognized for what they are.

There are two ways of making symbols or marks which can quickly and easily be distinguished from each other—by making them of different shapes and by making them of different colors. It is believed that differences in color are more easily and surely recognized than are differences in shape. It is therefore recommended that for the four groups of types four distinct colors be used.

The age-long recognition by men of gold as the most precious of the metals has resulted in a tendency for the average man to think of gold as a symbol of value. Gold therefore would seem to be the logical color to use for types of the first group, the basic types—holotypes, cotypes, paratypes, lectotypes, and neotypes. The University of California Museum now marks its holotypes with a distinguishing mark of this color. As far as the committee has been able to learn, no North American museum now uses golden symbols for any types belonging in groups other than group one. The committee therefore recommends the use of gold as the distinguishing color for the first group.

The committee is aware of the fact that many museums now mark their types of the first group with orange, red, green, or blue symbols. As it may be a long time before some of these museums adopt any other color for the distinguishing marks on their basic types, if they *ever* adopt another color, the committee is refraining from recommending the use of red or green markers for *any* group of types in the scheme here proposed. The committee strongly recommends, however, that all curators place either golden, orange, red, green, or blue marks on all their basic types. The adoption of this recommendation would, as far as the committee is aware, require no change in the color of the symbols now used by any North American museum for its basic types.

Silver is universally recognized as a symbol of value second only to gold. Only one American museum (that of the University of California), as far as the committee is aware, now uses silver symbols on its type specimens (paratypes and figured specimens), so that the adoption of this color to indicate types of the second group would lead to confusion and require a change in symbols in that museum alone. The committee therefore recommends that silver be selected as the distinguishing color for this group—that is, for supplementary types (plesiotypes, heautotypes, and allotypes).

As far as the committee has been able to determine, no North American museum now uses any color except red, green, and blue for its supplementary types. The committee therefore strongly recommends that no museum use in future any colors except silver, red, green, or blue for its supplementary types.

If the above four recommendations are adopted, the committee believes that we shall probably have attained to at least this much uniformity in our North American methods of marking: all fossils marked with golden, orange, silver, red, green, or blue symbols would be essential types, except those (probably few, if any) figured specimens at the University of California which were not either basic or supplementary types; all specimens bearing golden or orange marks would be basic types (the California Academy of Sciences uses orange to indicate paratypes); and all specimens carrying silver marks would be supplementary types (except the paratypes and nonsupplementary figured specimens at the University of California).

The use of gold, silver, orange, red, green, and blue colors for essential types leave us few colors for the unessential types, as several colors are so similar to those mentioned (yellow to gold, for instance) that it would not be wise to use them. If, however, we rule out white and black as improper for use in this connection because of their use for other labeling purposes (catalog numbers, etcetera), as it would be desirable for us to rule them out if we could, we find that we have no good colors left with which to designate our unessential types. This situation has made it difficult for the committee to decide what to recommend for use with the unessential types, and has led it to recommend that, until some one of the colors, red, green, or blue, is finally abandoned as an indicator of essential types by all North American museums, so that it can be used for unessential types, the unessential types be marked with the following symbols: for types of group three (unessential published types—figured specimens and cited specimens that are not supplementary types), a horizontal white arrow-head; for types of group four (unessential unpublished types—topotypes, metatypes, homeotypes, and ideotypes), a white disk. This means that all unessential types will bear either white arrow-heads or white disks. As no North American museum is known to the committee to use white arrow-heads or white disks in marking its fossils for any purpose, the adoption of these symbols would presumably cause no confusion.

So much for the colors to be used to indicate the different *groups* of type specimens. Now for the means of distinguishing the subdivisions of the four groups and their casts.

Let us consider first the subdivisions of group one, the basic types—holotypes, cotypes (or syntypes), paratypes, lectotypes, and neotypes. These fall naturally into three sets: first, the holotypes and cotypes; second, the paratypes; and, third, the lectotypes and neotypes. The committee recommends that diamond-shaped tokens be used for all basic types—holotypes, cotypes (or syntypes), paratypes, lectotypes, and neotypes—and that a black "H" be placed on the holotype diamonds, a black "C" or "S" be placed on cotype (or syntype) diamonds, a black "L" on lectotype diamonds, a black "N" (or less preferably "N H") on neotype diamonds, and a black "O" on paratype diamonds. It is assumed that all neotypes will be neoholotypes. If neocotypes or neosyntypes existed, they could be marked "N C" or "N S". Where symbols shaped other than as diamonds are now in use for basic types, the above letters may be added, even if the shape of the symbol is not changed.

As for the subdivisions of group two, the supplementary types—plesiotypes (or hypotypes), heautotypes, and allotypes, the committee recommends that plesiotypes and heautotypes and allotypes, which are only special kinds of plesiotypes), be marked by pyramidal tokens bearing the symbol "$\frac{P}{L}$" (a combination of "P" and "L"). If it is desired to distinguish heautotypes and allotypes, the letters "H" and "A" may be added to the "$\frac{P}{L}$" for the two types respectively. Where diamonds or other symbols not triangles are now in use, the letters suggested may be added to them, as in the case of basic types, even if the shapes of the symbols are not changed.

For the unessential types it is recommended that the letters 'Ci" and "F" be placed in black ink on the white arrow-head for cited and figured specimens respectively, and that the letters "T", "M", "H", and "I" be written in the same way on the white circles for topotype, metatype, homeotypes, and ideotypes. These letters also may be added to any shaped symbol, even though it be not an arrow-head or disk.

The system of marking here proposed has nowhere in it any duplication of letters and no duplication of symbols as between members of the four main groups. All basic types would be marked with diamonds (preferably golden in color, but permissably orange, red, green, or blue), with the addition of the black letters "H" for holotypes, "C" or "S" for cotypes or syntypes, "L" for lectotypes, "N" (or less preferably "N H") for neotypes or neoholotypes (and "N C" and "N S" for neotypes and neosyntypes, if such exist). All supplementary types would be marked with pyramids (preferably silver in color, but permissibly orange, red, green, or blue), bearing the black symbol $\frac{P}{L}$ (or $\frac{P}{L}$ H or $\frac{P}{L}$ A for heautotypes or allotypes, if desired). All unessential cited or figured specimens would be marked with white arrow-heads bearing the black letters "Ci" for cited specimens and F for figured specimens. All unessential unpublished specimens would bear white disks, on which would be added a black "T" for topotypes, "M" for metatypes, "H" for homeotypes, and "I" for ideotypes.

Thus the nature of the type will be indicated in three ways (by the color and shape of the token and by the letter it bears) in the case of all specimens marked exactly according to the suggestions here made by the committee, and will be marked in at least two ways (by the color of the tokens, with the two exceptions previously noted, and by the black letters) in the case of *all* types. The black letters can easily be added to any of the symbols now in use, and they are practically self-explanatory and are never duplicated.

The committee believes that casts which are obviously casts need no mark to indicate their artificial nature. On casts which might be mistaken for originals, the committee recommends that there be placed a white rectangle with the word "Cast" written on it in black (or, less preferably, a white square with the symbol "Ca" or "CA" written on it in black).

Finally the committee wishes to call to the attention of the members of the Society the undesirability of the practice of marking type specimens by attaching paper labels, because such labels are likely to become detached from their specimens, and desires to urge upon all curators the use of permanent paints and permanent inks for the labeling of such specimens. Type specimens are not merely of value to science; some of them (the essential

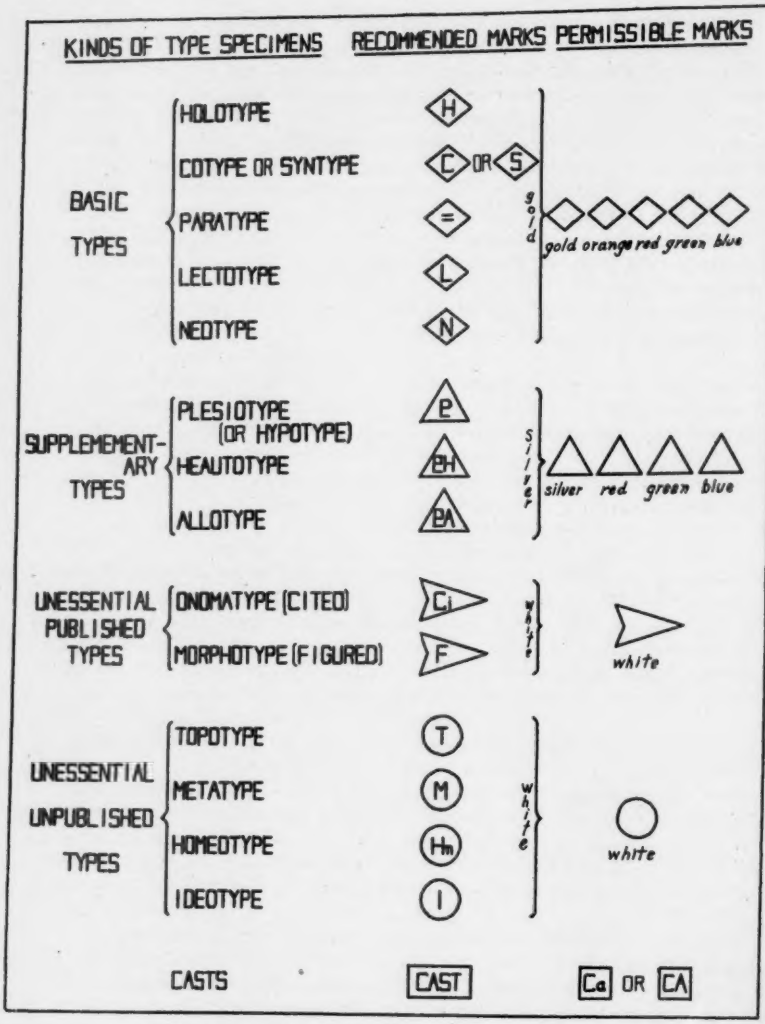

CHART OF TYPES AND RECOMMENDED MARKINGS

types) are absolutely necessary to science. They need to be so taken care of that they will not be lost and can always be recognized for what they are as types. They are always likely to become lost or their type character is likely to be forgotten—and many of them surely *will* be lost or have their type character forgotten—unless they are marked with permanent symbols whose nature can be easily recognized and understood.

Respectfully submitted for the committee.

B. F. HOWELL,
Chairman.

In accordance with the request of the Society, Dr. Howell has kindly furnished the following set of definitions and chart:

DEFINITIONS OF KINDS OF TYPE SPECIMENS

Holotype.—A *single specimen* on which a new species or subspecies is based.

Cotype (or Syntype).—Two or more specimens on which a new species or subspecies is based, *no one specimen* being designated as the *holotype.*

Paratype.—A specimen mentioned as having been used *in addition to the holotype* in preparing the original description of a new species or subspecies for which a holotype is designated.

Lectotype.—A *single specimen* selected by a *later worker* from the *original cotypes* of a species or subspecies as the *holotype of that species or subspecies* when the later worker finds that the *original cotypes do not all belong to a single species or subspecies.*

Neotype.—A specimen selected *to take the place of an original* type of a species or subspecies *when the original type has been lost.* A neotype may be either a *neoholotype* or a *neocotype.*

Plesiotype (or Hypotype).—A specimen *which was not used in the original description* of a species or subspecies, but which is *used for a later description or figure of it.*

Heautotype.—A specimen *figured by an author as an illustration* of a species or subspecies which had *previously been described as new by him.* This is really only one particular kind of a *plesiotype.*

Allotype.—A specimen chosen *by the original author* of a species or subspecies, *in addition to the* holotype, to show *some part of the body not shown in the holotype.* This is really only one particular kind of a *paratype,* if it is chosen *at the time when the species or subspecies is originally described.* If chosen *later,* it is a particular kind of a *plesiotype.*

Onomatype.—A specimen which has been *cited* in print (a *cited specimen*), but which has *not been used to illustrate anything not previously known about the morphology* of the species or subspecies to which it is referred.

Morphotype.—A specimen which has been *figured* in print (a *figured specimen*), but which has *not been used to illustrate anything not previously known about the morphology* of the species or subspecies to which it is referred.

Topotype.—A specimen collected from the *same horizon as the original holotype or cotypes* and from the *same locality as the originals,* or *within a few miles of that place.*

Metatype.—A *topotype identified by the original describer* of the species or subspecies to which it is referred, but *at a date subsequent to the publication of the original description.*

Homeotype.—A specimen that has been identified *by a worker who is recognized as an authority on the group of organisms to which it belongs,* after the specimen has been carefully *compared by him with the original type or types* of the species or subspecies to which it is referred.

Ideotype.—A specimen *collected from some other general locality than the original types* (that is, *not a topotype*) that has been *identified by the original author* of the species or subspecies to which it is referred *at a date subsequent to the publication of the original description.* This is like a *metatype,* except that it does *not* come from the *general locality from which the original type specimens of the species or subspecies were collected.*

PRESENTATION OF PAPERS

The regular program of papers was then resumed with a series bearing on vertebrate paleontology. The first two, dealing with fossil fishes, were given by the author and illustrated with lantern slides.

FOSSIL SNAPPER (FAMILY, LUTIANIDÆ) FROM THE MARIANNA LIMESTONE OF FLORIDA

BY WILLIAM K. GREGORY

(*Abstract*)

This fossil fish, which is the property of the Florida State Geological Survey, was discovered imbedded in limestone in a railroad cutting near Marianna, Florida. From many well preserved details of construction of the skull, teeth, backbone, and scales, it is evident that this specimen represents a fossil snapper, and that it was closely allied to the modern genus *Neomænis,* but differed in possessing one or two more vertebræ. Thus the percomorph family of snappers, which has apparently not hitherto been recorded as fossils, was already established along the Florida coast in Oligocene times.

RESTUDY OF THE SKULL OF PORTHEUS MOLOSSUS COPE

BY WILLIAM K. GREGORY

(*Abstract*)

A restudy of the skull of *Portheus,* based on several specimens in the American Museum and on photographs of exceptionally well preserved specimens loaned by Mr. G. F. Sternberg, had been the basis for a revised composite drawing of the lateral surface of the skull. The principal points noted were the possession of large, thin suborbital plates, similar to those of other primitive Isospondyli, and the presence of very large posttemporal bones not figured in place in previous figures. On the whole, the skull patterns closely approached that of the existing *Chirocentrus dorab,* as noted in Boulenger and Smith Woodward.

A stratigraphic subject of special interest to the vertebrate paleontologists was then presented by the author.

EROSION INTERVAL ABOVE THE LOST CABIN FORMATION AT BEAVER DIVIDE, WYOMING

BY HORACE ELMER WOOD, 2ND

(*Abstract*)

Granger and Sinclair found no evidence of any stratigraphic break from the Lost Cabin to the Uinta in the Beaver Divide section at the southern margin of the Wind River Basin, in central Wyoming, southeast of Lander. A reconnaissance along the new Riverton-Rawlins cut-off revealed a marked erosional unconformity above the Lost Cabin. The time interval represented may have been very brief, or more probably represents the equivalent of most or all of the Bridger, which formation may be entirely unrepresented in the Wind River Basin.

The same author then gave the results of his studies of fossil rhinoceros and their ancestors in the two following papers:

REVISION OF THE HYRACHYIDÆ

BY HORACE ELMER WOOD, 2ND

(*Abstract*)

Hyrachyus and its immediate relatives, an extinct group of subrhinocerine perissodactyls, are known only from the Eocene of western North America. They are an exceedingly conservative group, making little progress from the Lost Cabin to the Uinta. However, several contemporary series exist, and, in these, certain stages exist which can be called species. Some of these are useful index fossils. *Hyrachyus* seems to represent the little-changed descendants of the ancestors of all groups of rhinoceroses.

PROHYRACODON ORIENTALE KOCH, THE OLDEST KNOWN RHINOCEROS

BY HORACE ELMER WOOD, 2ND

(*Abstract*)

Prohyracodon orientale Koch, from Transylvania (Rumania), has been almost completely overlooked, due partly to its being based on scanty material in an isolated museum and more to inadequate description and figures. Restudy of the original material shows that it is unquestionably a true rhinoceros, primitive compared with most other rhinoceroses, but surprisingly progressive for its level, which appears to be Middle Eocene (Bartonian), or slightly older. It is older, therefore, than the oldest American true rhinoceroses and about as old as the oldest *Hyrachyus*.

The results of a detailed study of Devonian pelecypods with reference to stratigraphic correlation was next presented by the author.

FAUNAL STUDIES AND THEIR BEARING ON THE CORRELATION OF THE WISCONSIN DEVONIAN

BY ERWIN R. POHL

(*Abstract*)

The pelecypods of the Wisconsin Devonian are unique, not a single instance of unquestionable identification with forms elsewhere described having been found. This conclusion is supported by studies on the remainder of the Milwaukee fauna. Taxonomic relations point to a North Atlantic derivation, and, since the stratigraphic record in comparable Devonian formations to the east, south, and west is represented in much of its entirety, the assumption is reached that the invasion encroached from the north either by way of the south Laurentian-Saint Lawrence trough or by connection with a James Bay sea around the north of the Laurentian positive, in late Erian time.

The occurrence of marine sponge spicules in certain black shales and its significance was next discussed.

TETRACTINELLID SPONGE IN THE SUNBURY SHALE OF OHIO

BY WALTER S. BUCHER

(*Abstract*)

Spicules of a tetractinellid sponge were found by the writer in an exposure of Sunbury shale (lower Mississippian) north of Mineral Springs, in the northern part of Adams County, Ohio. They occur in small, more or less circular groups measuring about one inch in diameter. Most of the spicules of one group are monaxons, but a few are tetraxons with the characteristic anchor-shaped end. The longest of the spicules reach a length of half an inch.

In all groups the spicules lie in disordered arrangement. In all but one they are associated with conodont teeth and plates in a way which suggests that sponge spicules and conodonts here form part of the excrements of some nectonic animal.

Since all known tetractinellid sponges are marine and inhabit relatively shallow water, the occurrence of spicules of this group in the Sunbury shale is of interest in connection with the question of the conditions of sedimentation of this and the comparable earlier Ohio shales.

Three papers dealing with fossil plants closed the morning program. The first of these was discussed by Messrs. White, Mansfield and Wieland. Lantern-slide illustrations.

ROOTED LAND PLANTS IN A JURASSIC LIMESTONE

BY MAURICE BLACK [1]

(*Abstract*)

The lowest part of the Sundance formation, near Thermopolis, Wyoming, consists of a fine-grained, white limestone, which includes (about five feet

[1] Introduced by B. F. Howell.

from its base) a thin bed containing abundant stems and roots of the plant *Equisetites*. The impressions of the aerial shoots are quite clear, and, although they are decarbonized, possess the characteristics of the genus *Equisetites*. The arrangement of the roots can leave little doubt that the plants grew in the position in which they are now found. When it was in the condition of a soft carbonate mud, this limestone must have been covered with a fairly close growth of *Equisetites*, and thus offers a striking analogy with the present drewite flats of the Great Bahama Bank, which have no soil, but are covered with a growth of mangroves and other plants.

MESAVERDE CYCADEOIDS

BY G. R. WIELAND

(*Abstract*)

Field relations and occurrence, with general features of a new type of gigantic once-fruiting cycadeoid from about two-thirds up in the Mesaverde of the San Juan Basin region of New Mexico and Arizona.

CERRO CUADRADO PETRIFIED FOREST, PATAGONIA

BY G. R. WIELAND

(*Abstract*)

At the New Haven meeting Dr. E. S. Riggs of the Field Museum, Chicago, announced the discovery of this forest, in some respects the most remarkable petrified conifer forest yet discovered in the Western World. Its main features are discussed (following laboratory study) particularly with reference to the possibility of the discovery of such forests in North America.

At 1 p. m. the Society adjourned for luncheon. Meeting again at 2 p. m., the entire afternoon was devoted to the Symposium on Arctic and Antarctic Geology. The list of titles and the speakers, with abstracts of their remarks, are given in order below.

SYMPOSIUM ON ARCTIC AND SUB-ARCTIC GEOLOGY AND PALEONTOLOGY

INTRODUCTION

BY AUGUST F. FOERSTE

(*Abstract*)

This symposium is intended not only to indicate what already has been done in Arctic Geology, but also to focus attention on the problems still unsolved. Most Arctic expeditions were undertaken chiefly for geographical exploration. Scientific research, especially along geological lines, usually was accorded secondary consideration. This is readily understood, since the discovery of new lands attended with great hardship aroused widespread popular interest, while the purpose and value of scientific investigations was appreciated by much smaller numbers. Recently, however, the scientific results of Arctic explorations have received more consideration, and among the sciences to receive greatly increased attention is geology. The chief

difference between former and present methods of geological research in the Arctic is that in former days investigations were made chiefly where ships in their geographical explorations happened to make landings. Collections often came from widely distant localities, having no scientific connection with one another. Fossils often were poorly labeled both as to geographical locality and geological horizon. In fact, few data of a stratigraphical character ever were noted by earlier explorers. At present, on the contrary, landings often are made for the definite purpose of conducting specific geologic observations, and the stratigraphic relations of the fossils collected is given due consideration. One of the purposes of this symposium is to call attention to some of the geological problems that most need solution and to indicate where the opportunities for their solution appear most favorable.

CAMBRIAN OF THE ARCTIC REGIONS

BY C. E. RESSER

(*Abstract*)

Cambrian strata have thus far been found at only a few points actually within the Arctic Circle, but in the adjacent boreal regions such beds frequently appear along the southern shore of the formerly larger Arctic Ocean, along the margins of the Precambrian landmasses. This distribution substantiates the prevalent ideas regarding the permanency, extent, and importance of the Arctic Sea during Eopaleozoic times. Almost all the Cambrian faunas in the higher latitudes were apparently derived from the Arctic realm.

Outcrops of beds with the Middle Cambrian *Albertella* fauna occur on the Alaskan boundary north of the Yukon River. From the meager information in hand, it appears that next above are some strata with lower Upper Cambrian fossils. Eastward in the Mackenzie Valley several Lower Cambrian beds are succeeded by what appears to be a representative of the Middle Cambrian Stephen fauna, and this in turn by the widely distributed Upper Cambrian *Eoorthis* fauna.

In northern Greenland Koch's work has given us the most extensive information available for any Arctic district. Here both the Lower and Middle Cambrian are well represented, with some overlying beds that doubtfully belong to the upper division. All relationships are with western North American formations.

Northern Scandinavia has yielded a few Cambrian fossils from beds that seem to represent mainly formations occurring in the Southern Scandinavian region.

It now seems as if the strata in Nova Zembla described as doubtfully of Ozarkian age should rather be referred to the Upper Cambrian.

Recently many new finds have been reported in northern Asia and the sketchy reports indicate that only one or two of the numerous and widespread Cambrian outcrops have yielded faunas referable to the Atlantic seas as re-

corded in Scandinavia, but that most of their affinities are again found in western North America, a relationship due to their common Arctic origin.

ORDOVICIAN AND SILURIAN OF THE ARCTIC REGIONS

BY AUGUST F. FOERSTE

(*Abstract*)

The American Arctic includes Lower and Upper Ozarkian, Upper Canadian, Black River, Trenton, and Richmond strata; also formations of Lower, Middle, and Upper Silurian age. However, most of the data regarding these formations are very disconnected, and stratigraphical studies have been made at very few localities, chiefly along the northwestern coast of Greenland and along the southwestern coast of Ellesmereland.

Among the most widely distributed faunas in the American Arctic is that described first by Whiteaves from southern Manitoba, but found since also along the western side of Hudson Bay, on Baffin Land, and in northwestern Greenland. The fact that this fauna was identified by Whiteaves as Galena-Trenton and by Troedsson and Foerste as Richmond calls attention to an interesting problem. The Richmond may be regarded as a recurrence of a Mohawkian fauna; at least many of its species are closely similar to others found in the Mohawkian. How, then, in the absence of the intervening Cincinnatian, it is possible to determine whether an isolated fauna is Richmond or Mohawkian?

A similar problem is that presented by the Silurian fauna containing *Lissatrypa phoca*, ranging from Boothia peninsula on the northern margin of the North American continent to the northwestern part of Greenland. Here the Silurian affinities of many of the species are obvious, but Holtedahl calls attention to species whose nearest relatives are in the Keyser formation at the base of the Devonian.

The Racine fauna of Wisconsin and northern Illinois contains many elements suggestive of close relationship with the Middle Silurian of Gotland and of the Bohemian basin. On this account Weller drew paleogeographic maps that permitted a migration of these faunas across the Arctic. However, recent investigations have failed so far in discovering characteristic Racine or Gotlandian faunas in any part of the American Arctic or Sub-Arctic. Of course, this is only negative evidence, but it deserves consideration.

An axis of elevation, the Caledonian, extended during Silurian times in a southwesterly direction across the peninsula of Scandinavia and the northern part of Great Britain. Even during Ordovician times it appears to have been in existence, since the American type of Canadian and Mohawkian faunas extends as far east as Bear Island, between Norway and Spitzbergen, but is unknown on the European continent. In a similar manner, the Middle and Upper Silurian of the American Arctic is typically American, and does not show marked affinities with the European Silurian. These and other similar observations suggest that paleogeographic maps will gain greatly in value if based on a much better knowledge of Arctic and Sub-Arctic faunas than we possess at present.

PALEOGEOGRAPHIC SIGNIFICANCE OF CERTAIN ARCTIC AND SUB-ARCTIC DEVONIAN SECTIONS

BY E. M. KINDLE

(*Abstract*)

Small collections of Devonian fossils have been made by various expeditions from the Arctic Archipelago. The published reports on these, however, afford no satisfactory idea of the complete Devonian sections represented, with one exception. This is the Ellesmere Island section, which Per Schei studied and collected from while a member of the Second Norwegian Arctic Expedition, in the *Fram*, 1889-1902.

A Helderbergian fauna lies at the base of the Ellesmere Island Devonian section. Meyer[1] and Stephen Lowe[2] have described from it a brachiopod and coral fauna which includes such species as *Pentamerus pseudogaleatus* Hall, *Spirifer concinnus* Hall, *Eatonia medialis* Vanuxem var. The Middle Devonian fauna is represented in Series D by a fauna which includes *Productella arctirostrata*, *Spirifer gregarius*, and *Cyathophyllum cæspitosum*.

The marine beds with this Middle Devonian fauna pass into the sandy continental deposits of Series E, holding fish and plant remains. Kiaer, in his study of the fishes, and Nathorst, from the study of the plants, agree in referring Series E to the Upper Devonian. The fishes Kiaer finds more closely related to those of Scotland and the north of Europe than to the Scaumenac Bay and Catskill fishes.

The termination of this section by continental deposits thus indicates the shifting of the shoreline in Upper Devonian time west of its position in Middle Devonian times.

A small collection of marine Upper Devonian fossils from near the southwest corner of North Devon Island is important, in showing that the Upper Devonian sea was not a great distance west of Ellesmere Island. This is a collection of fossils made by Roald Amundson at Beechy Island, from which Holtedahl reports[3] *Schizophoria striatula*, *Atrypa reticularis*, and *Spirifer whitneyi* Hall var. *animasensis* Girty.

These clearly indicate an Upper Devonian fauna representing the marine equivalent of some part of Series E of Schei's Ellesmere section. The great thickness of Upper Devonian continental deposits in the southern part of Ellesmere Land and the evidence of a late Devonian marine fauna at Beechy Island afford grounds for drawing a north and south Upper Devonian shoreline across western Ellesmere Island and Devon Island.

The upper part of the Ellesmere Land section is comparable in its continual sediments with the Scaumenac Bay section in eastern Quebec. Both have red beds and conglomerates. Thin coal bands are present in each and fossil fish are the dominant forms in the Scaumenac beds, as in Schei's Series E. The contrasts in the faunas, however, are too great to suggest a continuous coastline, and a sea way south of Greenland, into the Hudson

[1] Report of the Second Norwegian Arctic Expedition, in the *Fram*, 1898-1902, No. 29.
[2] Report of the Second Norwegian Arctic Expedition, in the *Fram*, 1898-1902, No. 30.
[3] Report of the Second Norwegian Arctic Expedition, in the *Fram*, 1914, No. 32, p. 47.

Bay region, seems probable, by which the *Manticoceras intumescens* fauna may have passed freely between western Europe and America via the Greenland-Iceland-Shetland Island ridge.

The Abitibi River section, south of James Bay, is important in this connection because it includes a marine Upper Devonian fauna which is believed to be the time equivalent of a part of the Ellesmere Island continental deposits, and supports the probability of the Portage Sea extending north from the New York province across Hudson Bay to the western part of Devon Island and beyond.

The Upper Devonian Intumescens or *Buchiola retrostriata* fauna has nearly as great a north-south distribution in the MacKenzie Basin as it has in the New York and Alleghany region. The distribution of this fauna from New York through Iowa and the MacKenzie Valley is in striking contrast with the unlikeness of the eastern and western Middle Devonian faunas and suggests for the Upper Devonian a freedom of land and temperature barriers which was lacking during the Middle Devonian.

ORDOVICIAN, SILURIAN, AND DEVONIAN OF ALASKA[1]

BY EDWIN KIRK

(*Abstract*)

The Stratigraphic Units Represented.—On comparing the stratigraphic sequence of northwestern Alaska (Seward Peninsula), eastern Alaska (Yukon-Porcupine area), and southern Alaska (southeastern Alaska), we find that approximately the same stratigraphic units are represented. Lower, Middle, and Upper (probably) Ordovician, Middle and Upper Silurian, and Middle and Upper Devonian are all found in southeastern Alaska. In northwestern Alaska, Lower, Middle, and Upper (probably) Ordovician, Middle (probably) and Upper Silurian, and Middle Devonian are known. In eastern Alaska, Lower, Middle, and Upper Ordovician, Middle and Upper (probably) Silurian, and Middle Devonian are found; Upper Devonian was probably present, but has either not been found or has been removed by erosion.

Lower Ordovician.—In eastern and southeastern Alaska the horizon is represented by Deepkill graptolite faunas. In northwestern Alaska limestones carrying a small fauna consisting mainly of orthoid brachiopods represent the general horizon. There are but a few hundred feet of Lower Ordovician sediments. In eastern Alaska the thickness has been estimated at about 2,000 feet. In southeastern Alaska the combined Ordovician section has a thickness of probably not less than 10,000 feet.

Middle and Upper Ordovician.—The Middle and Upper Ordovician are combined for the reason that in some cases it is not known which is represented. In eastern and northwestern Alaska the Middle and Upper Ordovician have a thickness of but a few hundred feet, while in southeastern Alaska their share of the 10,000-foot total Ordovician runs up into several thousand feet.

[1] Published by permission of the Director, United States Geological Survey.

Silurian.—There are three well characterized Silurian horizons—Lower Niagaran, Upper Niagaran, and Upper Silurian. The Lower Niagaran is represented in southeastern Alaska by graptolite faunas and in eastern Alaska by graptolite faunas in part. The high Niagaran horizon is chiefly characterized by *Conchidium* of the type of *knighti* and is represented in southeastern and eastern Alaska. The upper Silurian has an extraordinary development in southeastern Alaska and is present in Seward Peninsula. In southeastern Alaska the sediments of Niagaran age have an aggregate thickness in excess of 5,000 feet, which includes a tillite having a maximum thickness of 1,000 feet, as seen. Between the measured Niagaran and the measured Upper Silurian, which consists of some 3,500 feet of limestones, lies a considerable series of limestones and argillites of unknown but considerable thickness. In eastern Alaska the Silurian faunas range through some 2,000 feet of limestones.

Middle Devonian.—The Middle Devonian is the most widespread of the Paleozoic units. In southeastern Alaska the sediments have a thickness of approximately 15,000 feet. The lowest well marked fauna carries *Calceola*, and the fauna agrees well with the *Calceola* fauna of Europe. The upper limit is marked by *Stringocephalus*. The Middle Devonian is well represented in eastern Alaska, although neither the highest nor lowest horizon of southeastern Alaska is present. Middle Devonian is present in western Alaska.

Upper Devonian.—The Upper Devonian has been recognized only in southeastern Alaska and in the Endicott Range, on the Arctic watershed at the north. In southeastern Alaska the Upper Devonian is represented by some 5,000 feet of sediments.

Summary.—In summing up the Ordovician to Devonian section, we find that in southeastern Alaska we have an aggregate of more than 38,000 feet of sediments. This may seem excessive, but the section has been carefully measured in units seldom less than 1,000 feet in thickness, and there is little reason to suspect repetition. On the contrary, some fairly considerable units have not been counted because of uncertainty as to their exast stratigraphic position. In the Yukon-Porcupine area the same stratigraphic range is represented by probably not over 5,000 feet of beds. In Seward Peninsula the total thickness is supposed not to be in excess of 2,000 feet. Compared with similar sections in western United States, the southeastern Alaska section is approximately three times greater in thickness than the maximum known in central Nevada. However, if the clastic Ordovician graptolitic facies of southern Idaho were combined with the Silurian and Devonian of central Nevada, the combined section would be approximately one-half the thickness of that of southeastern Alaska.

It is of interest to note that the Alaskan section is essentially that of western United States, so far as the time units represented are concerned. In turn we may compare both to those areas of the world that have been marked by moderately positive diastrophic tendencies. All such areas seem to be characterized by the presence of the middle (usually late middle) and upper portions of such systems as are represented. The only exception to be noted in Alaska is the Lower Ordovician.

The Paleozoic faunas of Alaska are chiefly notable in that, with the exception of such horizons as those of the upper Silurian that are sparsely rep-

resented elsewhere, they agree in content with faunas of equivalent age having enormously wide areal distribution. In regard to the Lower Ordovician, little can be said, owing to the scant faunas represented in the collections. The Lower Ordovician graptolite faunas, however, as well as those of later Ordovician age, are essentially those known everywhere. The Upper Ordovician fauna is practically that known throughout the Arctic regions, the Baltic, and in western North America from British Columbia to the Mexican border. A very similar fauna is found in Burma. The Niagaran faunas are unmistakably Niagaran, without marked peculiarities, though perhaps with more marked affinities with European faunas than are had with Niagaran faunas of eastern United States. The affinities of the Middle Devonian faunas are much closer with the Asiatic and European faunas than with those of eastern United States, but agree closely with equivalent faunas in western United States. The Upper Devonian faunas are in the main the typical world-wide forms and are very like those of western United States.

The great thickness of the southeastern Alaskan section may be accounted for in part by the presence of large amounts of clastic and volcanic material. The presence of this type of material in great development and its absence in equivalent horizons three or four hundred miles to the eastward is notable. A glacial origin seems certain for 1,000 feet or more of coarse conglomerates in the Silurian. Adopting the arguments currently used in favor of ice-rafting of boulders in the Paleozoic of the United States, conglomerates ranging in age from Ordovician to Triassic could with justice be ascribed to such action in southeastern Alaska. It is evident that the vast quantity of clastics and volcanic material could not have come from the eastward, where no signs of such materials are found in sediments of approximately equivalent age. One inevitably is forced to the conclusion that during the greater part of the Paleozoic there existed a considerable landmass of high relief and orogenic activity to the westward in what is now the northern Pacific Ocean. Available evidence seems to prove a similar landmass off the coast of California and Oregon, so for paleogeographic purposes we are faced with the necessity of placing a large landmass of vague outline in the midst of one of our outstanding negative areas.

CARBONIFEROUS OF ALASKA AND THE ARCTIC ARCHIPELAGO

BY GEORGE H. GIRTY

DEVONIAN AND CARBONIFEROUS OF THE ARCTIC EURASIA

BY I. P. TOLMACHOFF

(*Abstract*)

The Devonian was a very important moment in the geology of the Arctic Eurasia. At that time, or, more exactly, in Lower Devonian, were established the principal geological features of Arctic Eurasia. The old Euroasiatic continent, of which paleogeography it is impossible to have any definite idea, composed of Precambrian, Cambrian, Ordovician, and Silurian, was broken into a number of horsts of different sizes, separated by so many grabens. Since that time the horsts referred to never happened to be covered with sea-water again, and all later transgressions here were going on between the horsts.

Only within grabens were found and might be found Middle and Upper Paleozoic (up from the Devonian) marine sediments, as well as the Mesozoic and Tertiary ones. Where these sediments were found overlapping the borders of horsts, it was due to an overthrust, to a local diastrophism, and not to a regular succession in sedimentation. The Scandinavian Peninsula, in the most western part of Arctic Eurasia; the Chukchi Peninsula, at the extreme east of the same, and the Central Siberian Plateau, between these two, are three largest old horsts completely lacking Devonian and Carboniferous marine sediments. Between these principal horsts are located smaller ones—two of them west of the Central Siberian Plateau, which make parts of the Ural and Timan ridges, and two other ones east of it, found within the Verkhoyansk and Tas-Khaya-Khtakh ridges. Owing to their smaller size, they are often overlapped by newer Paleozoic (Devonian and Carboniferous) strata, which in this way take an immediate part in the construction of corresponding ridges along with old horsts making foundation of latter ones.

Devonian of the western part of the area under consideration is represented by continental strata, with plant and fish remains, found along the western coast of Norway and in its inner parts. It is Middle Devonian and lower horizons of Upper Devonian. Presumably, Upper Devonian sandstone beds are known also on the Kanian Peninsula. There is also a number of sandstone localities in eastern Finland and northwestern Russia which may be Devonian and partly have been considered as such, but partly belong to older formations. Continental Upper Devonian is known also in the Bear Island, showing a great faunistic similarity with corresponding strata of the Arctic America. A typical Old Red, amounting in its thickness to about 30,000 feet, is developed also in Spitsbergen Islands. The whole Devonian apparently is present here, but its fish fauna is different from that of the Bear Island, and thus belongs to a different province. Along with continental and fresh-water forms in the Devonian of Spitsbergen have been found also a few marine fossils, proving that the Devonian sea was not far from this area at the time of the origin of the Old Red. Except these localities, Devonian of the Arctic Eurasia and found in other Arctic islands is built up of marine sediments, often with rich fauna. Going from the west toward the east, one meets the Middle and Upper Devonian at first in the Timan Ridge. The Upper Devonian was found also in the Novaya Zemlya and in the Vaigach Island, in the latter case ranging from the upper part of Lower Devonian or from lower horizons of the Middle Devonian up to the Upper Devonian. The Devonian of the Arctic Ural is very little known, but probably it corresponds closely to that of the Timan Ridge. Within waste areas of Arctic Asia Devonian was found only in the eastern Siberia, on the right side of River Lena, north of the Polar Circle; in the Verkhoyansk Ridge, on the Dogdo and Kolyma rivers, and in Kotelny Island. Middle and Upper Devonian faunas of Arctic Eurasia are closely related to the corresponding faunas of northern America and of more southern regions of Europe and Asia. However, they belong to the well known universal type, which shows very wide and probably, numerous connections of different areas, which was, perhaps, dependent on, probably, shallow seas of that time having permitted migrations of faunas in any imaginable direction.

Carboniferous in its most complete form, in the western part of the Arctic Eurasia, is represented in the Ural Mountains, where have been found all three divisions of this system. It refers certainly to the more southern parts of this ridge, because its Arctic Carboniferous already discovered has been not known yet in some detail. However, as the Carboniferous of Ural is completely reproduced in Novaya Zemlya, it is quite reasonable to suggest that the Carboniferous in the intermediate areas has to be represented just in the same form. In a number of places north of the Polar Circle, as, for example, on the Ussa River, on the Jugor Shar Strait, were found here upper Carboniferous strata. Differently from Ural in the Timan Ridge, the lower Carboniferous is lacking, and the Devonian is transgressively covered here with the Mosquensis limestone of the middle Carboniferous. Exactly the same horizons of the Carboniferous as in the Timan Ridge are known in the Spitsbergen Islands and in the Bear Island, but in both these Arctic areas middle and upper Carboniferous are underlain with the plant-bearing sandstone series. On the Central Siberian Plateau are widely distributed coal-bearing strata corresponding in their age to those of the Kusnetzk coal fields of southern Siberia—that is, being of the uppermost Carboniferous, or Permian age. They were also indicated on the Chuckchi Peninsula and probably are present on the Kolyma River. Marine lower Carboniferous was discovered in Arctic eastern Siberia only in the Verkhoyansk Ridge, 65 degrees north latitude, but not investigated yet in some detail, geologically or paleontologically either. All other Carboniferous localities here, not numerous, indeed, have been correlated with the middle Carboniferous Mosquensis horizon. They were found on the Lena River, 72 degrees north latitude; in Kharaulakh Mountains east of the first locality, and on the western shore of Kotelny Island, north of 75 degrees north latitude, Carboniferous faunas of Arctic Eurasia are closely related to the corresponding North American faunas. Connection of the Euroasiatic Carboniferous seas with those of the North America is beyond question, but the way of this connection and of migration of different faunas has not been established yet definitely. Apparently, the most natural connection through the Atlantic used to exist only during the Lower Mississippian. Since that time it was broken and used to be restored only for a few short periods of time. A rather permanent connection is possible to imagine only through the Arctic region. It was not such an open-sea connection which was necessary to suggest for the Devonian, but probably it followed some rather limited ways. One of them was the Ural-Novaya Zemlya geosyncline; another, more hypothetical, one the Verkhoyansk geosyncline; the third one, still more hypothetical, the circumpacific. On the American side there are two geosynclines running toward the Arctic Ocean. One of them follows more or less closely the western shore and is the Cordilleran geosyncline; another corresponds to the Rocky Mountains.

TRIASSIC AND JURASSIC OF THE ARCTIC REGION

BY T. W. STANTON [1]

(Abstract)

Triassic.—The only Lower Triassic marine deposits known are in northern Siberia, near the mouth of Olenek River; on Kotelny Island of the New

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Siberian group, off the coast in the same general region, and possibly on the northern shore of Okhotsk Sea. At the two localities first named there is a well developed fauna, including many ammonites, which is referred to late Scythic—that is, to the upper part of the Lower Triassic. Its affinities are with the Indian Lower Triassic faunas.

The Middle Triassic also is very sparingly represented in the Arctic, being recorded only on the lower Jana and near the mouth of the Olenek, in northern Siberia, and on Spitsbergen, with meager faunas recorded in each case. The single reported occurrence of Middle Triassic in Alaska, based on a very small collection of fossils said to have come from Brooks Mountain, in the western part of the Seward Peninsula, needs further confirmation.

The much wider distribution of Upper Triassic sediments throughout the northern region indicates a great transgression of the sea at that time, and various stages and zones are recognizable in it. Marine Upper Triassic rocks are widely distributed in Alaska, cover large areas in northeastern Siberia, are present along Eureka Sound in the Arctic Archipelago, in Bear Island between Spitsbergen and Scandinavia, and are possibly present along the east coast of Greenland. Continental plant-bearing deposits of Rhætic or uppermost Triassic age also appear to be present in Siberia and Greenland.

The Upper Triassic Karnic, Noric, and Rhætic stages of the European classification are all recognized in the Arctic region. What appears to be a true Boreal fauna is found in the *Dawsonites* zone of early Karnic age, which extends as far south as British Columbia and is represented on Bear Island and possibly on Spitsbergen and Eureka Sound in the Arctic Ocean, and on the Yukon, in Alaska. This is succeeded by the rich ammonite fauna of the *Tropites subbullatus* zone, of Mediterranean and Indian affinities, which is represented in the Copper River region of Alaska and possibly on some of the islands of the Arctic Ocean.

The coral reefs of Cook Inlet and southeastern Alaska contain a fauna of early Noric age, certainly not Boreal in character, which is like that of the coral zone in the upper part of the Hosselkus limestone of northern California. The much more widespread *Pseudomonotis* fauna, characterized in California and Alaska by *Pseudomonotis subscircularis* and in Siberia by the similar *Pseudomonotis schotica*, is of later Noric age. This fauna is found in many parts of Alaska and over large areas in northeastern Siberia, as well as on Kotelny and other islands in the Arctic. A peculiar ammonite fauna containing *Pinacoceras* and *Cladiscites*, reported from Kotelny Island, has been tentatively referred to the Karnic, but it is here suggested that it is more probably of Noric age, since a similar assemblage recently found in Nevada has been shown to be Noric.

Most of the beds referred to the *Rhætic* in the Arctic region are continental plant-bearing deposits, but one area on Kuhn Island (east coast of Greenland) has been assigned to Rhætic on the evidence of *Rhynchonella fissicostata*.

Jurassic.—The break in the marine record of the Arctic which was begun in the Rhætic continued through a large part of the Lower Jurassic or Liassic. On the shore of Cook Inlet there is a brief record of Liassic marine deposition, and some of the volcanic rocks of the general region are believed to be of that age.

On the Alaska Peninsula, at Wide or Kialagvik Bay, the Kialagvik formation has yielded a fauna consisting largely of ammonites which has been referred to the upper Liassic, though there are some reasons for regarding it as basal Middle Jurassic. Leffingwell found representatives of the same fauna on the Arctic coast of Alaska in the vicinity of Canning River, and about the same horizon is represented at Point Wilkie, on the southern coast of Prince Patrick Island, where in 1849 Captain McClintock collected the ammonite described as *Ammonites mcclintocki*.

A Lower Jurassic (middle Liassic) fauna is also reported from the Arctic coast of Siberia west of the Lena River.

The *Middle Jurassic* is well exemplified with a rich fauna on Cook Inlet, Alaska. In fact, the southwest Alaska coast from the head of Cook Inlet to Wide Bay probably contains the best Jurassic section in North America. The Middle Jurassic, not very well characterized faunally, has been reported from the north coast of Siberia, from the east coast of Greenland, and from Franz Josef Land, King Charles Land, and Spitsbergen, in the Arctic Ocean.

In the *Upper Jurassic*, just as in the Upper Triassic, the faunas are more widespread and more characteristic throughout the Arctic region, and they are usually called Boreal or Arctic. At least they are Russian, though many of their characteristic elements wander very far from home before they become extinct. There is a succession of related ammonites—*Macrocephalites*, *Cadoceras*, *Quenstedtoceras*, *Cardioceras*, and *Amæboceras*—the later of which are associated with great numbers of *Aucella*, which also develops a succession of characteristic species extending up into the Lower Cretaceous.

The greatest transgression of the Jurassic sea upon northern lands took place near the beginning of the Upper Jurassic, in Callovian time, especially in the early Callovian, when the fauna was characterized by the abundance of ammonites belonging to the genera *Macrocephalites* and *Cadoceras*. Deposits with this fauna, in many places resting on pre-Jurassic rock, are widespread in northeastern Russia and in the Alaskan Peninsula, where they are very well developed. The *Cadoceras* fauna is also known on the Arctic coast of Siberia west of Lena River, on the New Siberian Islands, on Nova Zembla, where, like the other Mesozoic fossils reported, it is recorded from boulders only, on King Charles Land, on Spitsbergen, on Franz Josef Land, and on Jamesons Land, on the east coast of Greenland.

Next above the *Cadoceras* zone is the zone of *Quenstedtoceras*, which is placed by some European geologists in the Callovian and by others is considered basal Oxfordian. It is well represented in Russia, somewhat doubtfully so in east Greenland, and elsewhere in Arctic regions and Alaska, where the typical genus has not been found, though its place is doubtless in the lower part of the Naknek formation. The zone is of particular interest to American geologists because it is included in the earlier deposits (Ellis and Sundance formations) of the temporary epicontinental sea which came down from the north across British Columbia into the interior of North America, extending as far east as the Black Hills and as far south as Utah. The next younger *Cardioceras* zone, usually classified as Oxfordian, forms the larger part of the Sundance formation, extending to its top, and may be represented in the Ellis formation. At any rate, there seems to be no marine Jurassic younger than the *Cardioceras* zone in the Western Interior

region. Later deposits of Boreal type characterized by *Aucella* and by the ammonite genus *Amæboceras*, which with its type species, *A. alternans*, was formerly included in *Cardioceras*, are well represented in California as well as in the Arctic regions and Russia, but they are not found east of the Sierra Nevada in the United States. These late Jurassic beds, always characterized by certain species of *Aucella* and sometimes containing *Cardioceras*, *Amæboceras*, and other genera of ammonites, are widespread in northern Russia, northern Siberia, Alaska, the Arctic islands, such as Nova Zembla, Spitsbergen, King Charles Land, Franz Josef Land, and the east coast of Greenland. Some of these late Jurassic *Aucella* faunas extend far southward by way of British Columbia and Oregon to California and are known as far south as Coahuila and San Luis Potosi, in Mexico. The faunas from the Callovian on to the end of the Jurassic are apparently genuine Arctic or Boreal faunas. At least they have been dispersed across or around the Arctic Sea, whether they actually originated in it or not.

Casual mention has been made of continental deposits with coal and land plants in the Arctic region. There are large areas consisting chiefly of such deposits in Siberia, in Alaska, and on many of the islands. The more or less incomplete floras brought back from them have been assigned to the Rhætic and to several subdivisions of the Jurassic. Some of them also are most probably Cretaceous. There is urgent need for more thorough stratigraphic studies, supplemented by or in connection with areal mapping, so that these floras may be definitely assigned to their proper places in the stratigraphic column and correctly interpolated in the succession of marine faunas. Future explorations in the Arctic regions, resulting in more complete and more usefully placed collections, more detailed stratigraphic studies, and possibly unexpected discoveries of new faunas and floras and of the true relations of old ones, may greatly change our present conception of the Mesozoic of the Arctic.

CRETACEOUS OF THE ARCTIC AND SUB-ARCTIC REGIONS

BY JOHN B. REESIDE, JR.

(*Abstract*)

The only widespread Cretaceous deposits of the Arctic are the so-called "*Aucella* beds," usually assigned to the earlier Neocomian (Valanginian). They are recorded from central Russia; the Petschora Valley of northern Russia; Nova Zembla; along the Siberian coast from the Yenissei to the Yana, interbedded with coal-bearing rocks in the east; the Anadyr Basin; Alaska; the Mackenzie Valley, and the northeast coast of Greenland. The "*Aucella* beds" mark a widespread transgression.

Later Lower Cretaceous marine deposition is probably recorded by the marine Kennicott formation of southern Alaska and possibly also by the nonmarine Corwin formation of northwestern Alaska. The relations of these deposits to those of other regions is not yet clear. In Greenland the nonmarine Kome beds of the central west coast are believed to be Aptian or Albian.

Upper Cretaceous deposits are much scattered and unrelated in age and origin. Float of Cenomanian age is recorded between Chatanga and Anabara

rivers, in Siberia. In the Anadyr Basin marine Cenomanian of Indo-Pacific origin is followed by nonmarine beds. In Alaska Upper Cretaceous is much more restricted than Lower Cretaceous, and it is possible that most of the present-day mountain areas were above water. Beds believed to represent both earlier and later Upper Cretaceous time occur in southern and western Alaska, including both marine and nonmarine deposits; others on the north slope are not definitely placed. The marine faunas are dominantly of Indo-Pacific origin. In Canada deposits along the middle Mackenzie seem to be of Turonian (Benton) age and possibly in part of later age. On the central west coast of Greenland the Atane and Patoot beds, both in part marine and in part nonmarine, are of late Upper Cretaceous age. The faunas seem most closely related to those of the Interior Province of North America, but the manner of connection is entirely conjectural.

Extended speculation as to Arctic paths of migration and sources of faunas seems hardly justified by present knowledge. More information is needed from practically all the regions where Cretaceous deposits are known, and further search for new localities is desirable, though perhaps much light will be shed on the general problem by further work on the faunas of the regions well below the Arctic circle.

GRAPTOLITES OF ARCTIC AREAS

BY RUDOLF RUEDEMANN

(*Abstract*)

The writer distinguishes between pure graptolite shales with large numbers of species and genera of graptolites, such as the Normanskill shale, and the mixed graptolite shales, containing but few species of graptolites, associated with other fossils, as the Utica shale. The former beds are held to have been deposited in geosynclines and in marginal continental basins and the graptolites to have been of oceanic habitat, having been carried into the basins from the oceans; the latter beds to be epicontinental in origin and their graptolites to be provincial in habitat, having evolved and persisted in the epicontinental sea.

The graptolite faunas of northwest Greenland are of middle Deep Kill (upper Beekmantown or Canadian) and of late Lower Silurian (Gala-Tarannon or Clinton age). Their relationships are with European forms in the Silurian and generally with North Atlantic forms in the Ordovician (Canadian). They point to connection with the North Atlantic by way of the Caledonian geosyncline as constructed by Holtedahl (1920)—that is, as passing from north Greenland in a semicircle over Scandinavia, Great Britain, and the North Atlantic to America, where it continues in the Appalachian geosyncline. Various large graptolite faunas entered the latter geosyncline from the North Atlantic in Canadian and Ordovician time and some in Silurian time, in the latter without, however, extending beyond the northeastern portion.

The Arctic Archipelago has so far not furnished any graptolite faunas.

Alaska and the Yukon territory have afforded lower and upper Deep Kill graptolites (Wrangell Island, Prince of Wales Island), Normanskill graptolites (Mount McKinley region, Prince of Wales Island, Yukon-Alaska boundary, Beaver River district of Yukon), graptolites of Snake Hill age

(El Capitan Passage, on Prince of Wales Island), and Silurian graptolites (such of Llandovery age, at the Porcupine River of the Yukon territory, and such of about Clinton age, on Prince of Wales Island and the near-by Dall Island). Much larger and better preserved collections have, however, been found in British Columbia. These western faunas have a strong Australian element, pointing to the Pacific Ocean as their normal habitat and to the deposition of the shales in marginal continental seas or geosynclinal troughs.

From Arctic Asia, only an as yet undescribed fauna is known, discovered on Bennett Island, north of the New Siberian Islands, of about Upper Canadian (Beekmantown) age.

Finally, there is urged careful search by geologists for graptolites in shales, especially dark ones, in Arctic regions, and especially the utmost care is asked in distinguishing the faunules, in collecting, as to their successive horizons, as some horizons may be only a few inches thick.

CLIMATIC SIGNIFICANCE OF ARCTIC FOSSIL FLORAS

BY E. W. BERRY

(*Abstract*)

Fossil plants have been found at six general horizons in the Arctic, namely: late Devonian, Mississippian, late Triassic, late Jurassic and early Lower Cretaceous, Upper Cretaceous, and Eo-Oligocene. They are frequently associated with coal seams, and this, together with roots in place in the under clays, the presence of fresh-water diatoms, mollusks, and aquatic beetles, proves that the plants grew near where they are found fossil and were not drifted from lower latitudes.

Maps were shown with the various localities indicated. The distribution of these localities around the pole conclusively discredits the hypothesis, now fashionable in certain quarters, that there has been a change in position of the pole. A botanical analysis of the floras shows clearly that the term tropical, so frequently applied to them, is highly improper, and that they are, for the most part, distinctly cold temperate. The associated petrified woods, with the single exception of the *Dadoxylon* from the Mississippian of Spitsbergen, show well marked seasonal rings.

Detailed comparisons of these Arctic floras with contemporaneous floras from lower latitudes, especially in the case of the younger, post-Paleozoic floras, show unmistakable evidence for the existence of climatic zones. It was further shown that these northward extensions of temperate floras in the past were all contemporaneous with or immediately followed times of unusually widespread continental submergence and sea extension, and that they lived under the domain of oceanic as opposed to continental climatic conditions.

It was concluded that low lands and expanded seas were amply sufficient to account for the necessary ten to fifteen degrees northward swing of isotherms demanded by the botanical character of the floras. This, with the concomitant alterations in wind and current circulation, combined with Brooks's meteorological results, are considered to account for all of the observed facts.

ARCTIC PALEOGEOGRAPHY AND FAUNAL MIGRATIONS

BY E. O. ULRICH

At 6 p. m. the Society adjourned for the day.

SESSION OF FRIDAY, DECEMBER 28

At 9:15 Friday morning the reading of papers of the general program was resumed, with President Foerste presiding.

PRESENTATION OF PAPERS

Evidence resulting from recent field-work on ancient man in Florida was presented by the author and illustrated by lantern slides.

FURTHER INVESTIGATIONS ON THE PROBLEM OF FLORIDA ANCIENT MAN

BY J. W. GIDLEY

(Abstract)

This paper is based on the continued work done last winter at the Melbourne, Vero, and other localities in Florida. By new methods of working the deposits, it was found that the upper, or number 3, bed of Sellards is of swamp plus wind-blown sand origin, and that it is barren of remains of any land fauna, either extinct or recent. The uneven contact zone between it and the underlying number 2 bed, however, contains an abundant fauna, found in natural association with human remains and artifacts, including potshreds. This fauna has a more modern aspect than that of the number 2 bed, but is not thought to be recent. It was discovered that this uneven contact plane is not due to stream-current erosion, as formerly assumed, but to numerous circular basin-shaped depressions of unknown origin. This surface shows every evidence of having been lived on by both animals and man before the swamp areas were established. It was formerly thought that the deposits of the number 2 bed were also of stream-current origin, but abundant evidence was found to show they are the result of long-continued accumulation of wild-blown sands. The number 2 bed showed no evidence of any intrusion in it of material of later age than the beds themselves. The fauna of this zone is distinctly Pleistocene and, while Aftonian in general aspect, may represent a later phase of the Pleistocene. The number 2 bed is fossil-bearing at all levels, and human remains and artifacts have been found in it in undisturbed association.

Many of the members now being present, President Foerste called the Society to order for the business session of the twentieth annual meeting. The report of the Council was given first.

REPORT OF THE COUNCIL

To the Paleontological Society, in twentieth annual meeting assembled:

The following reports give an outline of the Society's business as transacted at the nineteenth annual meeting at Cleveland, Ohio, and by correspondence since then.

Secretary's Report

To the Council of the Paleontological Society:

The Secretary's report for the year closing December 26, 1928, in brief, is as follows:

Meetings.—The Proceedings of the nineteenth annual meeting, held at Cleveland, Ohio, December 29-31, 1927, have been printed in volume 39, number 1, pages 281-312, of the Bulletin of the Geological Society of America.

The Council's proposed nomination for officers for 1929 was mailed to the members in March, 1928, with the announcement that the twentieth annual meeting would be held at New York City, at the invitation of the American Museum of Natural History, Columbia University and New York University.

Membership.—The Society has lost one member, Dr. Bashford Dean, by death during the year. One member has resigned. Sixteen have just been elected and twenty nominations await action. One member, H. N. Coryell, has just been elected to fellowship in the Geological Society of America. The total number of members, with these various changes, at the end of 1928 will be 361.

Publications.—The Proceedings for 1927 and two articles, totaling 52 pages, have been published in the Bulletin of the Geological Society of America during the year.

Pacific Coast Section.—This section of the Paleontological Society met on Saturday, March 3, at the University of California, when a program of nineteen papers was given. The titles and abstracts of these papers are given on a later page.

Respectfully submitted,

R. S. Bassler,
Secretary.

Treasurer's Report

To the Council of the Paleontological Society:

The Treasurer begs to submit the following report of the finances of the Society for the fiscal year ending with December, 1927:

CREDITS

Cash on hand December 28, 1927	$1,248.42	
Membership dues collected for 1928	441.00	
Interest, Connecticut Savings Bank	47.39	
		$1,736.81

DEBITS

Secretary's office:		
Secretary's allowance (voucher 1)	$100.00	
Clerical aid (voucher 3)	25.00	
Office expenses (voucher 2)	61.79	
		$186.79
Treasurer's office:		
Treasurer's allowance (voucher 4)	25.00	
Office expenses (voucher 5)	19.55	
		44.55
Publication:		
Geological Society of America, circulars, et cetera, for Cleveland Meeting (voucher 6)	17.82	
Wetzel Bros., programs for Pacific Coast Branch (voucher 7)	22.50	
		40.32
Miscellaneous:		
Checks returned for lack of funds	6.00	6.00
		$277.66
Balance on hand December 26, 1928		$1,459.15

Bills outstanding:

Pacific Coast Branch for affiliation fee to the American Association for the Advancement of Science for 1926-28	$15.00
Geological Society of America, for 200 reprints of pages 281-312 of volume 39 of the Bulletin	13.31
	$28.31

Outstanding dues:

Members 2 years in arrears—5	$10.00
Members 1 year in arrears—24	72.00

Very truly yours,

CARL O. DUNBAR.

APPOINTMENT OF AUDITING COMMITTEE

With the completion of the Council's Report, President Foerste appointed Messrs. J. J. Galloway and E. H. Sellards as a committee to audit the Treasurer's accounts.

ELECTION OF OFFICERS AND MEMBERS

The ballot for officers for 1929 and the election of the members was next in order. The results of the balloting were as follows:

OFFICERS FOR 1929

President:
E. C. CASE, Ann Arbor, Mich.

First Vice-President:
B. F. HOWELL, Princeton, N. J.

Second Vice-President:
CHESTER STOCK, Pasadena, Calif.

Third Vice-President:
JOS. A. CUSHMAN, Sharon, Mass.

Secretary:
R. S. BASSLER, Washington, D. C.

Treasurer:
CARL O. DUNBAR, New Haven, Conn.

Editor:
WALTER GRANGER, New York City

NEW MEMBERS FOR 1929

FRANK A. BECKWITH, Delta, Utah.
FRANK M. CARPENTER, Bussey Institute, Forest Hills, Boston, Massachusetts.
ALBERT S. DUCKWORTH, 915 College Hill, Cape Girardeau, Missouri.
M. A. HANNA, Gulf Production Company of Texas, Houston, Texas.
BRUCE M. HARLTON, 1733 South Yorktown Avenue, Tulsa, Oklahoma.
WINIFRED MCGLAMERY, Department of Geology, University of North Carolina, Chapel Hill, North Carolina.
MARGARET MORREY, Department of Geology, Vassar College, Poughkeepsie, New York.
SIEMON W. MULLER, Department of Geology, Stanford University, Stanford, California.
JOHN B. OWEN, Clinton, Missouri.
JOHN R. SANDIDGE, Princeton University, Princeton, New Jersey.
ERNEST R. SMITH, 309 Greenwood Avenue, Greencastle, Indiana.
GEORGE F. STERNBERG, Kansas State Teachers' College, Hays, Kansas.
E. M. UPSON, Gulf Production Company of Texas, Fort Worth, Texas.
LIONEL W. WIEDEY, Box 761, Palo Alto, California.
JAMES S. WILLIAMS, 103 Geology Building, University of Missouri, Columbia, Missouri.
CHARLES W. WILSON, JR., Princeton, New Jersey.

NEW NOMINATIONS AND ELECTION TO MEMBERSHIP

The following twenty nominations for membership, received after the ballot had been printed, were then submitted, with the approval of the Council, to the Society for action.

ED. J. BARRAGY, Department of Geology, University of Iowa, Iowa City, Iowa. Invertebrate paleontology. Proposed by A. O. Thomas and R. S. Bassler.

ALEXANDER CLARK, 522 North Newlin Avenue, Whittier, California. Invertebrate paleontology. Proposed by W. P. Woodring and E. L. Furlong.

GLENN SCOTT DILLÉ, Department of Geology, University of Iowa, Iowa City, Iowa. Invertebrate paleontology. Proposed by A. O. Thomas and R. S. Bassler.

ROBERT H. DOTT, Geological Department, Mid Continent Petroleum Corporation, Tulsa, Oklahoma. Micropaleontology. Proposed by Bruce H. Harlton, E. O. Ulrich, and R. S. Bassler.

HERSCHEL L. DRIVER, 630 West Palm Drive, Glendale, California. Micropaleontology. Proposed by W. P. Woodring and William S. W. Kew.

CARROLL LANE FENTON, Old Tech Building, University of Cincinnati, Cincinnati, Ohio. Invertebrate paleontology. Proposed by E. O. Ulrich, and R. S. Bassler.

MILDRED ADAMS FENTON, Old Tech Building, University of Cincinnati, Cincinnati, Ohio. Invertebrate paleontology. Proposed by E. O. Ulrich and R. S. Bassler.

CHARLES LEWIS GAZIN, California Institute of Technology, Pasadena, California. Vertebrate paleontology. Proposed by W. P. Woodring and E. L. Furlong.

LLOYD G. HENBEST, Peabody Museum, Yale University, New Haven, Connecticut. Invertebrate paleontology. Proposed by Carl O. Dunbar and Charles Schuchert.

JESSE HARLAN JOHNSON, 1220 Cheyenne Street, Golden, Colorado. Late Paleozoic and Mesozoic invertebrates. Proposed by F. M. Van Tuyl and John B. Reeside, Jr.

LEROY FERRIS KINDLE, Department of Geology, Rutgers University, New Brunswick, New Jersey. Devonian invertebrates. Proposed by W. J. Sinclair, R. M. Field, and B. F. Howell.

LOWELL R. LAUDON, Department of Geology, University of Iowa, Iowa City, Iowa. Invertebrate paleontology. Proposed by A. O. Thomas and R. S. Bassler.

SHEPARD WETMORE LOWMAN, 1307 South Saint Louis Avenue, Tulsa, Oklahoma. Micropaleontology. Proposed by Bruce H. Harlton, E. O. Ulrich, and R. S. Bassler.

RALPH L. LUPHER, California Institute of Technology, Pasadena, California. Invertebrate paleontology. Proposed by W. P. Woodring and E. L. Furlong.

JOHN HAVILAND MAXSON, 488 North Marengo Avenue, Pasadena, California. Vertebrate paleontology. Proposed by W. P. Woodring and E. L. Furlong.

HOWARD A. MEYERHOFF, Department of Geology, Smith College, Northampton, Massachusetts. Invertebrate paleontology. Proposed by J. J. Galloway and R. S. Bassler.

ARTHUR K. MILLER, 206 Geology Building, University of Missouri, Columbia, Missouri. Invertebrate paleontology. Proposed by E. B. Branson, M. G. Mehl, and Carl O. Dunbar.

BERNARD NETTLETON MOORE, 1026 West Twentieth Street, Los Angeles, California. Invertebrate paleontology. Proposed by W. P. Woodring and E. L. Furlong.

EDWIN M. ROWSER, Department of Geology, University of Iowa, Iowa City, Iowa. Invertebrate paleontology. Proposed by A. O. Thomas and R. S. Bassler.

ALDRED SCOTT WARTHIN, JR., Department of Geology, Columbia University, New York City. Micropaleontology. Proposed by J. J. Galloway and E. O. Ulrich.

After a motion to suspend the By-Laws had been voted, the election of these twenty nominees to membership was approved.

ELECTION OF CORRESPONDENTS

President Foerste then called attention to four students of European paleontology and stratigraphy whose work was of such superior quality that the Council recommended their consideration for election as Correspondents. These nominations are as follows:

DR. A. ÖPIK, University of Tartu, Tartu, Esthonia.
DR. CHRISTIAN POULSEN, Mineralogical Museum, Copenhagen, Denmark.
DR. ERIC A. STENSIÖ, Naturhistoriske Riksmuseum, Stockholm, Sweden.
DR. ELSA WARBURG, University of Upsala, Upsala, Sweden.

After a brief presentation of the attainments of these four scientists, their election as Correspondents followed by unanimous vote.

NEW BUSINESS

The request of the Treasurer that the funds of the Society be kept in two accounts, savings and checking, in the same bank, in New Haven, instead of in two separate banks, as heretofore, was then explained to the Society. This move for greater facility in caring for the funds, previously approved by the Council, was therefore voted upon favorably.

The necessity of increased facility for the publication of paleontological papers was then brought up by the Council and a discussion of the subject followed. This was followed by a vote that the President appoint a committee to investigate the probable cost and possible ways of financing the publications for report at next meeting. President Foerste appointed Messrs. Howell (chairman), Parks, and Twenhofel as the committee, with power to enlarge their membership as found desirable.

The announcement was then made that David White had been nominated representative of the Society in the Division of Geology and Geography of the National Research Council for the three-year period beginning July 1, 1929, in succession to Dr. L. W. Stephenson, whose term of office expires on that date.

With the conclusion of the business meeting, the Society proceeded to the reading of papers, with Dr. Foerste in the chair.

PRESENTATION OF PAPERS

A great reduction in the number of species of Pennsylvanian amphibia was described in the first paper, in which the anatomic structure of these fossils was illustrated by lantern slides.

TAXONOMY AND MORPHOLOGY OF SOME PENNSYLVANIAN AMPHIBIANS

BY ALFRED S. ROMER

(*Abstract*)

A large number of amphibians have been described from the Pennsylvanian of North America. Almost all, however, are very poorly known, and it is difficult to determine the structure or systematic position of many types. Recent European work on related forms and some new specimens offer a basis for an attempt to synthesize this material, with the elimination of numerous species and genera. For example, more than fifty amphibians have been described from one small pool at Linton, Ohio, but it is probable that less than half that number of forms was actually present.

The occurrence of marine fossils in glacial deposits indicating the possibility of a different origin of certain phases of such rocks was then discussed and illustrated with lantern slides by the author.

MARINE FOSSILS IN THE PERMIAN TILLITE OF BRAZIL

BY RUDOLF RUEDEMANN

(*Abstract*)

A collection of fossils from the Permian tillite of Sao Paulo, Brazil, sent by Dr. Derby a decade ago to Dr. Clarke for study, but left untouched, has been found to contain prevailingly large coprolites, composed of fish bones and scales, fish scales belonging, according to W. L. Bryant, to the Paleoniscidæ; teeth of Crossopterygians, large patches of tissue of spicules of lyssakine sponges, and brachiopod shells, belonging to the genera *Lingula* and *Orbiculoidea*. These marine fossils are found in a black shale, intercalated in the tillite.

The possibility that at least a portion of the Permian tillite of Brazil is submarine drift deposit, such as forms today around the poles, is discussed.

An unusually complete skull, showing the details of the nasal region and the palate of a new form of Phytosaur from the Upper Triassic beds of Howard County, Texas, formed the subject of the next paper, which the author illustrated by lantern slides.

NEW FORM OF PHYTOSAUR FROM THE TRIASSIC OF TEXAS

BY E. C. CASE

There was then described, and illustrated with lantern slides, a specimen of the bird dinosaur *Struthiomimus* from the Belly River Cretaceous of Alberta, consisting of the fore part of the body only, remarkable in that the head is almost perfect and by far the best of the Ornithomimidæ yet unearthed. Discussed by Messrs. Gilmore and the author.

NEW SPECIES OF STRUTHIOMIMUS

BY W. A. PARKS

Stromatoporoid reefs in the Middle Devonian of Michigan formed the subject of the next paper, illustrated with lantern slides.

TRUE REEF FORMED BY STROMATOPOROIDS

BY MILDRED A. FENTON

(*Abstract*)

In limestones of Traverse age, near Petoskey, Michigan, there is a dome-shaped reef consisting chiefly of fragmental stromatoporoids of the genus *Stromatopora*. Other domes on the quarry floor indicate the presence of similar reefs at lower levels. The stromatoporoids are found to be in the contracted state, thus preventing specific identification; they must have become calcified shortly after death. Most of the fragments are angular, as are those of the few corals found in the reef.

In the following paper evolutionary trends in the brachiopod *Spirifer* were described and illustrated by the author, who compared them with similar trends among other fossil groups.

APPARENT ORTHOGENETIC EVOLUTION IN THE GENUS SPIRIFER

BY CARROL LANE FENTON

(*Abstract*)

In the brachiopod genus *Spirifer* there are several pronounced evolutionary trends involving characters both of the shell as a whole and of minute sculpture. In the *S. varians* and related gentes, two of these trends are closely correlated; they lead from wide shells, with numerous, strong plications ornamented by striæ, to narrow, long ones, whose plications are few and weak and whose ornamentation consists of pustules. This sequence is repeated in subgentes and even species, at various levels, and without discernible relationship to the environment. There is little fluctuation and no evidence of heterogenetic heritable variation.

These trends are closely comparable to trends found among mollusks, arthropods, and even vertebrates. They accord with the theory of ortho-

genesis by senescence, and to a considerable extent support Child's suggestion of phyletic senescence through decreasing metabolism.

The next paper gave the details of new occurrences of Devonian fishes in Missouri, Utah, and Wyoming.

NEW LOCALITIES FOR DEVONIAN FISHES

BY E. B. BRANSON

(*Abstract*)

During the summer of 1928 geological students from the University of Missouri collected numerous fragments of fish bones from the Jefferson (Devonian) limestone near Logan, Utah. *Dinichthys*, *Acanthaspis*, and *Ptyctodus* are the genera represented. The *Acanthaspis* remains seem to be indistinguishable from those of the Columbus limestone of Ohio, and the *Ptyctodus* seems to be *calceolus*, the species so widespread in Middle and Upper Devonian in the Mississippi Valley.

Mr. N. H. Brown and his sons, of Lander, Wyoming, found what seem to be *Dincthys* and *Acanthaspis* bones at the base of the Madison limestone near Lander, Wyoming. The bones are in a sandstone which seems to be a remnant of a Devonian formation.

Near Columbia, Missouri, numerous Dinichthyd plates and one nearly complete Dinichthyd skull have recently been found.

There was then presented by E. B. Branson, in the absence of the author, a short account, with lantern slide illustrations, of an interesting assemblage of blastoids from the early Mississippian of Missouri.

BLASTOIDS FROM THE CHOUTEAU LIMESTONE

BY R. E. PECK[1]

(*Abstract*)

The Chouteau (Kinderhookian) blastoids represent nine species belonging to the genera *Cryptoblastus*, *Codaster*, and *Orbitremites*.

Cryptoblastus, formerly thought to have originated in younger rocks, is far the most abundant, and in the collection studied by the writer there are about 50 specimens of it to one of any other genus. *Cryptoblastus* is represented by six species, *Codaster* by two species, and *Orbitremites* by one species.

None of the Chouteau species has been reported from any other formation, but *Schizoblastus haynesi* Clark, from the Madison of Montana, may be the same as *Cryptoblastus romeri* Shumard.

In the absence of Dr. Matthew, G. B. Simpson then read the following paper which was illustrated by charts and discussed by F. B. Loomis:

[1] Introduced by E. B. Branson.

RECLASSIFICATION OF THE ARTIODACTYL FAMILIES

BY W. D. MATTHEW

(*Abstract*)

The customary grouping of the families of Artiodactyla is unsatisfactory as regards the extinct forms of the older Tertiary. The following arrangement is suggested, which it is believed better represents the natural affinities of the different families as shown by the characters of teeth and feet.

Dichobunidæ Entelodontidæ	*Palæodonta.* With primitive bunodont teeth and subdidactyl or didactyl feet.
Dicotylidæ Suidæ Hippopotamidæ	*Hyodonta.* Specialized bunodont teeth, triangular canines, tetradactyl feet.
Anthracotheriidæ Anoplotheriidæ Caenotheriidæ Oreodontidæ	*Ancodonta.* Bunoselenodont to selenodont teeth, tetradactyl feet.
Xiphodontidæ Camelidæ	*Tylopoda.* Precociously didactyl feet, selenodont teeth, premolars compressed and subsequently reduced.
Amphimerycidæ Hypertragulidæ Tragulidæ Cervidæ Giraffidæ Antilocapridæ Bovidæ	*Pecora.* Didactyl pes with navicular and cuboid united. Manus tetradactyl, becoming didactyl. Cannon bones of characteristic type. Upper incisors and usually canine lost, lower canine incisiform.

A most interesting discovery in vertebrate paleontology formed the next subject. Lantern slide illustrations and discussion by Messrs. Riggs and Romer.

REMARKABLE GROUND SLOTH

BY R. S. LULL

(*Abstract*)

Description of specimen found in a volcanic vent in Dona Ana County, New Mexico, and now in the Peabody Museum at Yale. In this region are extensive lava flows, some of which are geologically recent. Aden Crater, an extinct volcano having on one side a fumarole which forms a natural death trap and enlarges into two chambers, in one of which, at a depth of 100 feet, there was found, embedded in bat guano, this remarkable specimen. So fully is it preserved that the bones are held in articulation by their original sinews. The hands and feet still bear the horny claws, and portions of the head

and body still retain patches of hide with traces of hair, notably one on the pelvis. The specimen is practically entire, except for certain sternal ribs and the tip of the tail. It represents an immature, although nearly full grown, individual of *Nothrotherium* cf. *shastense* known from the Rancho la Brea, a locality in Wheeler County, Texas (*N. texanum* O. P. Hay) and elsewhere. A food ball was also found which will give a clue to the actual food of the animal.

A discussion of the paleontological zones and stratigraphy of the Permian of western Texas followed.

FAUNAS AND CORRELATION OF THE PERMIAN OF TRANS-PECOS, TEXAS

BY ROBERT E. KING

(Abstract)

Permian rocks are present in trans-Pecos, Texas, principally in the Glass Mountains, the Delaware-Guadalupe Mountains, the Diablo Plateau (including the Hueco and Diablo Mountains), and in the vicinity of Shafter. They comprise the thickest and most complete Permian sections in North America, and contain very prolific faunas of normal marine type, in contrast with the dominantly molluscan fauna of central Texas, Oklahoma, and Kansas. Successive faunas show progressive stages of evolution which are of great value in correlation. Most important for purposes of correlation are the ammonoids, which occur in the Glass Mountains in seven district faunas, each at a different stratigraphic level. The lowest ammonoid fauna, the *Uddenites* fauna, is of very earliest Permian age, while the highest, the *Waagenoceras* fauna, is of late middle Permian age. The upper 2,500 feet of limestone, which contains no identifiable ammonoids, is probably of upper Permian age.

In the Diablo Plateau the fauna of the lower part of the Permian section, so varied elsewhere in the region, consists mainly of pelecypods, gastropods, *Composita mexicana*, and *Pugnax*. This is the same facies as the Permian limestone (Gym and Upper Naco) of southwestern New Mexico and southeastern Arizona. Near the New Mexico boundary layers of gypsum interfinger with this limestone, representing a gradation into the Chupadera facies of central and southeastern New Mexico. The upper formations of trans-Pecos Texas (Delaware Mountain sandstone and Capitan) apparently are not represented in the Chupadera, as they seem to thin out a few miles north of the Texas-New Mexico boundary. Nor do these formations appear to have equivalents in the Permian of north-central Texas or Oklahoma, where the highest ammonoid horizon, the Blaine, contains ammonoids practically identical with those of the Leonard (*Perrinites*) rather than those of the Delaware Mountain sandstone and the Word (*Waagenoceras*). Species of the "San Andres," Kaibab, and Phosphoria faunas occur mainly in the Leonard formation of the Glass Mountains section.

New Cambrian Crustacea were then described and illustrated with lantern slides.

NEW LOWER AND MIDDLE CAMBRIAN CRUSTACEA

BY C. E. RESSER

The final paper of the morning program dealt with the evidence of the Taconic Revolution in the region of Delaware Water Gap.

STRATIGRAPHIC EVIDENCE FOR THE TACONIC DISTURBANCE IN EASTERN PENNSYLVANIA AND NEW JERSEY

BY BRADFORD WILLARD

(*Abstract*)

Structural evidence has been presented recently as proof of a late Ordovician disturbance in eastern Pennsylvania. The disturbance is believed to be equivalent to the Taconic disturbance. This paper attempts to show that the interpretation of the origin of the Middle and Upper Ordovician and Lower Silurian formations in the region of the Delaware Water Gap supports the evidence advanced from a study of the structures.

Adjournment for luncheon occurred at 1 p. m.

At 2 p. m. the report of the Committee to Audit the Treasurer's Accounts, attesting their correctness, was given. The Society then proceeded with the symposium dealing with stratigraphic and paleontologic evidence concerning the Paleozoic-Mesozoic boundary of the Rocky Mountain region. Doctor Mehl presided and, after an introduction outlining the general subject, announced the speakers in the following order:

SYMPOSIUM ON THE PALEOZOIC-MESOZOIC BOUNDARY OF THE ROCKY MOUNTAIN REGION

STRATIGRAPHIC EVIDENCE FOR THE PALEOZOIC-MESOZOIC BOUNDARY, SOUTHERN PROVINCE

BY JOHN B. REESIDE, JR.

STRATIGRAPHIC EVIDENCE FOR THE PALEOZOIC-MESOZOIC BOUNDARY, NORTHERN PROVINCE

BY E. B. BRANSON

LOWER MESOZOIC BOUNDARY AS INDICATED BY THE MESOZOIC INVERTEBRATES

BY T. W. STANTON

EVIDENCE OF PLANT REMAINS ON THE UPPER LIMITS OF THE PALEOZOIC AND LOWER MESOZOIC

BY G. R. WIELAND

NEW EVIDENCE ON THE CLOSE OF THE PALEOZOIC IN WYOMING

BY CARL C. BRANSON

VERTEBRATE EVIDENCE ON THE LOWER LIMITS OF THE MESOZOIC

BY M. G. MEHL

JOINT SESSION WITH THE GEOLOGICAL SOCIETY OF AMERICA

At 4:15 p. m. the Society adjourned to meet in joint session with the Geological Society of America for the consideration of the stratigraphic papers on the program of the latter Society. The following papers were then given, Dr. Foerste presiding:

TULLY FAUNA AT THE BASE OF THE BLACK SHALE IN EAST-CENTRAL KENTUCKY

BY T. E. SAVAGE

(*Abstract*)

East of the Cincinnati anticline, in Estill and Powell counties, Kentucky, the Upper Devonian strata are represented by a bed of hard black, laminated shale which ranges in thickness up to 135 or more feet. In the lower 10 or 15 feet of this shale there are lenses and bands of rather fine sandy, magnesian limestone, from 2 or 3 inches to as much as 8 or 10 inches thick, interbedded with the black shale. At the base of the shale there is commonly a single layer of somewhat sandy, magnesian limestone, called by Foerste the Duffin layer, which ranges from 2 to 5 feet in thickness. This Duffin layer belongs to the age of the black shale deposition, as is shown by the fact that in some places a thickness of a few feet of black shale is present beneath it.

The Duffin layer, and some of the lenses of sandy, magnesian limestone ten or more feet above the base of the black shale, furnished such fossils as *Ambocoelia* cf. *umbonata*, *Camarotoechia* cf. *sappho*, *Chonetes* cf. *mucronatus*, *Hypothyris cuboides*, *Leiorhynchus quadricostatus*, *Martinia subumbona*, and *Spirifer pennatus* var. *tulliensis*.

Of these species, *Hypothyris cuboides* is thought to indicate an age corresponding to that of the Tully of New York, and the associated species are not inconsistent with such a correlation. This would indicate that the black shale deposition in this part of Kentucky began as early as Tully time.

CORRELATION OF THE LOWER CAMBRIAN SEDIMENTS AT NAHANT, MASSACHUSETTS, WITH THE BAR HARBOR SERIES

BY CHARLES WILSON BROWN

(*Abstract*)

Throughout northeastern New England there are widespread but sporadic occurrences of the fine-grained, even-bedded, purplish, quartzose flagstones, which point to an era at the beginning of the Paleozoic of abundant though quiet sedimentation throughout this area. The lithologic responses of these rocks to slight or great metamorphism under similar conditions but in different localities are peculiar, constant, and easily recognized. In spite of the separation of these sediments by the irregularities of the Maine coastline and by extensive batholithic intrusions, a careful study of the different occur-

rences of these flagstones at Nahant, Biddeford, North Haven, Mount Desert on the coast and about Bangor, Houlton, and North Anson Falls in the interior, warrants the presentation of these tentative conclusions.

SILURIAN OF THE CENTRAL APPALACHIANS

BY CHARLES K. SWARTZ AND FRANK M. SWARTZ

(*Abstract*)

The authors have been engaged for a number of years in the study of the Silurian formations of the region between the Delaware River and northeastern Tennessee. Sections, many of them closely placed, will be shown exhibiting the character of the Silurian formations of this region and a correlation will be given based upon the sections and their faunal zones.

Some of the results believed to be established are the following: The Clinch sandstone of Safford, the upper division of the Massanutten sandstone of Virginia, the Tuscarora of Maryland and central Pennsylvania and the Shawangunk of eastern Pennsylvania are continuous. The Clinton may be traced throughout the region, its Keefer sandstone member being widely persistent. The Sneedsville limestone of Tennessee is continuous with the Tonoloway limestone of Maryland and central Pennsylvania and the latter, in part at least, with the Bossardville of eastern Pennsylvania and New Jersey.

The relations of the marine McKenzie, the Wills Creek and the continental Bloomsburg are shown and the correlation of the latter with the Vernon and High Falls red shale of New York suggested.

COMANCHEAN REPTILES OF KANSAS, OKLAHOMA, AND TEXAS

BY CHARLES M. GOULD

(*Abstract*)

In 1893, and again in 1895, the writer discovered bones of Plesiosaur in the Kiowa shales of Clark County, Kansas. These fossils were named by S. W. Williston. In 1909 Pierce Larkin discovered fragments of a bone of a dinosaur in the Trinity sandstone near Atoka, southern Oklahoma. During the past twenty years dinosaur tracks have been found in the Glenn Rose formation, of middle or upper Trinity age, in various counties in Texas. The last discoveries of tracks of this kind were made in Kinney County, Texas, during the past summer. These tracks, which are described herein, are 21 inches long and average 15 inches broad. The animal had a stride of 5 feet 3 inches.

HILLSBORO SANDSTONE OF OHIO

BY J. ERNEST CARMAN AND ERNEST O. SCHILLHANN

(*Abstract*)

The Hillsboro sandstone, exposed in Highland County, Ohio, was named by Orton who gave sections showing it either interbedded in the upper part of the Niagaran or resting on Niagaran. Prosser later published sections showing it interbedded in both Niagaran and the overlying Monroe.

The authors of this paper have shown that all the exposures previously interpreted as sandstone layers interbedded in the Greenfield and the Niagaran dolomites are really more or less irregular masses of sandstone completely enclosed in the dolomites not more than 30 feet below the Silurian-Devonian disconformity which in this region truncates the Greenfield and Niagaran dolomites. The other exposures are at the horizon of the disconformity resting on either the Greenfield or the Niagaran.

The Hillsboro sandstone therefore includes two types of deposits of the same age: (1) discontinuous sand deposits laid down on the post-Silurian erosion surface on either the Greenfield or the Niagaran; (2) sand that was washed down into and filled existing cavities and open joints beneath this erosion surface in either the Greenfield or the Niagaran. By this interpretation, it is younger than the erosion interval which came some time after the formation of the Greenfield dolomite of late Silurian and older than the Ohio shale of upper Devonian, which, in this region, lies next above the Silurian-Devonian disconformity. It is in the same hiatus as the Sylvania sandstone of early Devonian age of northwestern Ohio, but this hiatus in Highland County extends farther downward and farther upward.

NEW TRIASSIC FOSSIL LOCALITY

BY MALCOLM R. THORPE

(*Abstract*)

In October, 1926, a slab of red Triassic sandstone, bearing a natural cast of a dinosaur footprint, was discovered a few miles east of New Haven in an area which had hitherto produced no fossils of any kind. This footprint was figured and described by Professor Lull as *Anchisauripus tuberosus* (E. Hitchcock). The locality was at the site of the new dam of the New Haven Water Company, at North Branford, about 8½ miles slightly north of east of New Haven, Connecticut. Subsequent exploration at this site resulted in the discovery of two more tracks (*Anchisauripus* and *Eubrontes*) in the red and gray sandstone strata, while in the black shale several fossil fishes (*Semionotus* and *Catopterus*) were collected, together with fragments of fossil wood.

In connection with this new reservoir an inlet tunnel was bored a continuous distance of 13,503 feet, in a nearly east-west direction, under Sea Hill and the Sugar Loafs, the tunnel being known as the Sugar Loaf Tunnel. The West Portal of this tunnel is approximately 2 miles north of the dam. The tunnel penetrates the Triassic posterior shales and sandstones throughout its entire length, cutting across about 275 feet of the formation.

Fifty-six footprints were recovered from the tunnel and from the tunnel spoil representing seven genera (*Batrachopus*, *Anchisauripus*, *Gigandipus*, *Eubrontes*, *Grallator*, *Triaenopus*, and *Shepardia*) and twelve species, including one new species and one new subspecies. Five species, apparently hitherto unreported from Connecticut, represent parasuchians, theropod dinosaurs, and possibly amphibians. They were both bipedal and quadrupedal forms.

This new locality extends the southward geographic range of the footprints by some 10 miles, Middlefield being hitherto the farthest southerly area where prints have been definitely found.

There are three horizons carrying considerable quantities of fossil wood. The black shale at the site of the dam, the tough gray sandstone at the West Portal, and the black shale, much higher, in ascending order. The first is characterized by what seems to be *Loperia*, the second by *Baiera*, while the uppermost horizon contains huge quantities of wood, but in extremely fragmentary and crushed condition. In all horizons the wood is more or less carbonized and cut by numerous transverse fractures filled by calcite, or in some cases perhaps by silica. It is wholly unlikely that these are ferns of any kind but it is certain that they are solid stems. They must therefore indicate left over Cordaite, or early Gymnosperm tree vegetation.

ALTERNATING OSCILLATORY MOVEMENT IN THE CHAZY AND LEVIS TROUGHS OF THE APPALACHIAN GEOSYNCLINE

BY RUDOLF RUEDEMANN

(*Abstract*)

The mapping of the Capitol District has clearly brought out the fact that a threefold, possibly a fourfold, reversal of movement took place from Lower Cambrian time to Middle Ordovician time in the two adjoining Chazy and Levis troughs of the Appalachian geosyncline, in such a fashion that the eastern trough was submerged when the western was emerged, and vice-versa.

The cause of these alternating warpings of the troughs is seen in the interplay of the "oceanic spread" and "continental creep," two opposite forces that, acting one from the east and the other from the west, were able to affect the nearest troughs differentially.

DETAILS IN THE EARLY HISTORY OF THE NASHVILLE DOME

BY M. G. MEHL AND WALTER F. POND

(*Abstract*)

The Nashville Dome of Central Tennessee seems to have had an early history similar in the main to that of the Cincinnati arch as a whole. Although there is evidence of several slight emergences and deformation of the dome area in Mohawkian and Cincinnatian times, the first pronounced elevation came at the end of the Fernvale, Richmond. At that time the dome must have had an elevation of several hundred feet. The excavation of canyons to a depth of 150 feet or more about its southeastern margin in Lincoln County, Tennessee, is an evidence of this. Following a Mid-Silurian submergence, during which there were deposited on the deeply eroded surface between 300 and 400 feet of sand, clay, and lime, there was another marked elevation of the southeast side of the dome. In Lincoln County the Chattanooga formation rests on a peneplaned surface that involves late Ordovician and completely truncated, thick, Silurian series.

Read by title, so that the next paper could be presented at this point.

NEW FAMILY OF SOUTH AMERICAN PLIOCENE MAMMALS

BY E. S. RIGGS

DEVONIAN STRATA IN WEST TEXAS

BY N. H. DARTON

(*Abstract*)

During the past summer Devonian fossils were discovered in black shale on the west slope of Franklin Mountains northwest of El Paso, the first ones of Devonian age reported in Texas. The shale lies in Fusselman limestone (Silurian) and is overlain by limestone of Permian age. It probably represents the Percha shale which is present between Silurian and early Mississippian limestones in southern New Mexico. The outcrop area appears to be very small owing to overlap and faulting.

Read by title.

TEXAS EOCENE: CORRECTIONS

BY GEORGE HALCOTT CHADWICK

(*Abstract*)

(1) Midway of Medina County, Texas. The State Survey bulletin on this county subdivides the Midway beds into the Elstone and Squirrel Creek formations, in ascending order. Extended field-work has shown that these subdivisions have been inverted, the Elstone actually being the higher, and that, in consequence, the two have been badly confused; also that there is possibly a third member locally present above the Elstone glauconitic limestone.

(2) Carrizo-Wilcox contact. In the same bulletin, the Carrizo sandstone is described and mapped as highly transgressive across the Wilcox beds, but all of the occurrences so claimed have proved to be either Reynosa (Uvalde) beds or plain *caliché*. Since this asserted unconformity has proved disconcerting to classification and has been widely quoted, the correction is an important one.

At 6 p. m. the Society adjourned, meeting again at 7 o'clock, at the Hotel Astor, for the annual dinner of the Geological Society of America and affiliated societies.

SESSION OF SATURDAY, DECEMBER 29

Meeting at 9 o'clock, with Dr. Foerste presiding. The following papers, in the absence of their authors, were read by title:

PRESENTATION OF PAPERS

GEORGETOWN FORMATION OF CENTRAL TEXAS AND ITS FORT WORTH EQUIVALENT AS DETERMINED BY PALEONTOLOGICAL INVESTIGATION

BY R. H. CUYLER

PLEISTOCENE PROBOSCIDEANS WITHIN THE CUMBERLAND PLATEAU IN KENTUCKY

BY W. R. JILLSON [1]

[1] Introduced by R. S. Lull.

VARIABILITY IN FORAMINIFERA AND ITS BEARING ON NOMENCLATURE

BY JOSEPH A. CUSHMAN

(*Abstract*)

Variability in the foraminifera has many sources. So-called "variation," consisting of difference in microspherical and megalospheric forms, developmental stages, ecologic conditions, etcetera, must be taken into consideration in determining the specific and even generic standing of any form in question, and many individuals are necessary to adequately describe a species.

STRUCTURAL CHARACTERS IN FORAMINIFERA AND THEIR BEARING ON RELATIONSHIPS

BY JOSEPH A. CUSHMAN

(*Abstract*)

Study of characters often given clues to relationships not previously suspected. A series of such characters may be more or less accelerated in development and some of them skipped, so that those forms showing full characters must be used in preference to others for determining relationships.

The first paper of the morning gave an account of the discovery and structure of the first known foraminifera from the Devonian of the United States.

FORAMINIFERA FROM THE DEVONIAN OF IOWA

BY A. O. THOMAS

Professor Thomas then presented in succession the following papers, all illustrated and prepared by graduate students working under his direction:

STUARTELLA, A NEW GENUS OF DEVONIAN TEREBRATULOIDS

BY C. H. BELANSKI

CRINOID FAUNA OF THE GOWER (NIAGARAN) OF CEDAR COUNTY, IOWA

BY E. M. ROWSER

PRELIMINARY REPORT ON THE STRATIGRAPHY AND PALEONTOLOGY OF THE CAMBRIAN (DEADWOOD) OF THE BLACK HILLS

BY ED. J. BARRAGY

PRELIMINARY REPORT ON THE STRATIGRAPHY AND PALEONTOLOGY OF THE MISSISSIPPIAN FORMATION OF THE BLACK HILLS

BY GLENN S. DILLÉ

The final paper of the meeting was devoted to the evolution of Paleozoic foraminifera as based on their wall structure. Illustrated by lantern slides.

WALL STRUCTURE OF PALEOZOIC FORMINIFERA AND ITS BEARING ON THE PHYLOGENY OF FORAMINIFERA

BY J. J. GALLOWAY

(*Abstract*)

The material of which the walls of Foraminifera are constructed and the structure of the walls have been considered by nearly every student of Foraminifera since 1854 to be of first importance in the classification of Foraminifera. The material may be (1) chitinous, as in the Lagynidæ (Gromiidæ), which are rarely if ever found as fossils; (2) siliceous, as in some deep-water Miliolidæ, and in some Jurassic and Carboniferous forms, possibly due to silicification; (3) calcareous and perforate, as in the Rotaliidæ, Globigerinidæ, and many other families; (4) calcareous and imperforate, or porcellaneous, as in the Miliolidæ and other families; and (5) agglutinated or arenaceous, consisting of foreign particles cemented together, as in the Astrorhizidæ and Textulariidæ.

Most classifications of Foraminifera, as those of Schultze, Reuss, Schwager, and Brady, have been in the form of keys, with no weight laid on the geologic range or phylogeny. Phylogenetic classifications, such as those of Neymayr, Rhumbler, and Eimer and Fickert, start with the single-chambered, arenaceous forms and derive all other forms from them.

It is obvious that post-Paleozoic forms have been evolved from Paleozoic forms. In 1876 Brady considered nearly all Paleozoic Foraminifera to have arenaceous or "sub-arenaceous" walls. Two questions need answer in determining the phylogeny of Foraminifera: (1) which Paleozoic forms are calcareous and which arenaceous, and (2) were calcareous forms evolved from arenaceous forms or were arenaceous forms evolved from calcareous forms?

Although several genera of undoubted Foraminifera are found in the Cambrian, Ordovician, and Silurian, not one is arenaceous; all are calcareous, apparently imperforate. In the Devonian, four or five genera are known, which appear to be calcareous and imperforate, and mention has been made of finding some arenaceous forms. In the Mississippian there are several genera of the Endothyridæ, the Nodosinellidæ, and the Spirillinidæ, all of which have calcareous walls. The wall structure is indistinct, possibly due to recrystallization of the calcite, but where it is distinct it is alveolar, similar to that of *Fusulina*. *Endothyra* has been interpreted as arenaceous by most authors, as calcareous and perforate by Möller, and as both arenaceous and calcareous by Cushman and by Ozawa.

In the Pennsylvanian and Permian there are known some sixty-five genera of Foraminifera. These genera fall into three groups: (1) clearly calcareous and non-arenaceous forms, including the Spirillinidæ, the Nodosinellidæ, *Cornuspira*, some Rotaliidæ, and all the Fusulinidæ, embracing 40 genera; (2) doubtfully arenaceous forms with calcareous walls, including the Endothyridæ, some Textulariidæ, *Ammodiscus*, and *Trepeilopsis*, embracing 20 genera; and (3) clearly arenaceous forms, including *Tolypammina*, *Hyperamminoides*, *Saccammina*, *Morœinella*, and *Reophax*—5 genera. Some authors even consider the walls of *Fusulina* to be made up of agglutinated, foreign particles.

Considering the earlier appearance and greater abundance of calcareous forms in the Paleozoic, as well as the ontogeny, structure, and ecology of

later forms, it seems more probable that agglutinated Foraminifera have been derived from calcareous forms with secreted walls. Phylogenies interpreted from the two different starting points are quite different.

Program of the Pacific Coast Branch

The regular annual meeting of the Pacific Coast Branch of the Paleontological Society was held on Saturday, March 3, 1928, in Bacon Hall, University of California, Berkeley, in affiliation with the Cordilleran Section of the Geological Society of America, with Ralph W. Chaney as Secretary.

ELECTION OF OFFICERS

The election of officers for the coming year resulted as follows:

President, W. D. Matthew, University of California

Vice-President, W. P. Woodring, California Institute of Technology

Secretary, H. G. Schenck, Stanford University

Starting at 9 a. m., the following program occupied a day's session:

PRESENTATION OF PAPERS

TERTIARY ROCKS OF PART OF CHEHALIS VALLEY, WASHINGTON

BY THOS. J. ETHERINGTON

(*Abstract*)

The rocks of this area are all of Tertiary age, with a maximum thickness of 12,000 feet. The sedimentary rocks are all fossiliferous, but the writer's work has been concentrated upon the Wahkiakum formation, of middle Eocene age. These collections are now being studied and comparisons are being made with the fossils of similar age from Oregon to California, in the Museum of Paleontology, University of California.

DISTRIBUTION IN TROPICAL AMERICA OF TURRITELLAS OF THE PHYLUM OF TURRITELLA OCOYANA

BY W. P. WOODRING

(*Abstract*)

Large, strongly keeled *ocoyana*-like Turritellas have an extensive distribution in tropical America. So far, they have been found in Mexico, Colombia, and Venezuela, all on the Caribbean side, and in Peru, Ecuador, Darien, Chiriqui Province, Panama, and Lower California, on the Pacific side. In the Caribbean region these Turritellas are found in two Middle Miocene zones, the lower corresponding to the Cercado formation of the Dominican Republic and the upper corresponding to the Gurabo formation of the Dominican Republic and the Gatun formation of the Panama Canal Zone. On the Pacific side they apparently are confined to the upper zone.

Though six names have already been proposed for these tropical Turritellas, they clearly fall in the *ocoyana* phylum and they may eventually be considered as representing a subspecies of *ocoyana*. This phylum appears in California as an invader. According to available evidence, it reached the Pacific from the Atlantic by way of the Central American seaways. Perhaps it developed from a lower Miocene stock represented by *Turritella subgrundifera* of the Chipola formation of Florida.

VERTEBRATES FROM PLIOCENE BEDS IN FISH LAKE VALLEY, NEVADA

BY E. RAYMOND HALL

SOME EOCENE COLLECTIONS FROM SOUTH AMERICA

BY BRUCE L. CLARK

DISCOVERY OF THE BAIRD MISSISSIPPIAN FAUNA OF CENTRAL OREGON

BY EARL L. PACKARD

(*Abstract*)

Paleozoic fossils were early discovered in eastern Oregon by Condon. Other discoveries by Lindgren, Washburn, and Livingston have added somewhat to the knowledge of the Upper Paleozoic of Oregon. Recent field-work by the writer in the region south of Ochoco Range led in 1925 to the discovery of several areas of Paleozoic rocks. The more important of these lies southwestward from Suplee Postoffice. This area has yielded a characteristic Baird Mississippian fauna, including the species *Productus striatus* Fisher and the *Productus giganteus* Martin.

PLEISTOCENE ELEPHANT ON SANTA ROSA ISLAND, CALIFORNIA

BY CHESTER STOCK AND E. L. FURLONG

(*Abstract*)

The occurrence of elephant remains in Pleistocene deposits on Santa Rosa Island was recorded as early as 1873. Recent paleontological investigations conducted by the California Institute of Technology on this member of the Santa Barbara Islands has yielded further remains of Proboscidea. The occurrence and nature of the materials are described and their significance indicated.

SUMMARY OF THE WEST COAST SUBGENUS TROPHOSYCON

BY HOYT RODNEY GALE

(*Abstract*)

The types of all four of the species of nodose fig-shells so far described on the west coast are said to have come from Middle Miocene formations. Paleontologists have endeavored to distinguish these species and at the same time to identify specimens from later horizons with some of them. Much confusion has resulted and one worker has proposed to include them all in a single species. It is now found possible, however, to distinguish one of

the mid-Miocene species from California and Oregon and another from Washington, besides a new species from the upper Miocene and a new species and variety from the lower Pliocene of California. It is thought that Trophosycons will now be more useful for correlation purposes.

AFFINITIES OF SOME NEW PALEOCENE MAMMALS FROM THE FORT UNION BEDS

BY WILLIAM D. MATTHEW

GEOLOGICAL INTERPRETATION OF ENDEMISM IN THE CALIFORNIA COAST RANGE FLORA

BY HERBERT L. MASON

(*Abstract*)

Endemic tree species in the modern forests of the California Coast ranges appear to fall into two forest associations, the Monterey Forest and the Redwood Forest.

The Monterey Forest occurs in small colonies along the coast of California, at such points as the Mendocino Coastal Plain, Point Reyes Peninsula, Monterey, Ano Nuevo Point, San Simeon Bay, La Purissima Hills, and insular southern California. Many of these discontinuous areas have plants that are peculiar to them or are found only in one or two of the areas. We have as examples the Monterey cypress, the Torrey pine, the Catalina ironwood, and many others.

The geological history of these areas indicates that they have been land in most cases since Cretaceous and Eocene time, forming islands in an extensive archipelago. Those now on the mainland were joined during Pleistocene uplift. Their endemic cast is therefore probably of insular origin, arising through isolation of the floras on insular masses. On those that are now joined to the mainland the endemic nature has been somewhat ameliorated by competition and invasion of continental floras. Those areas still remaining insular retain a very high percentage of endemism.

Endemism in the Redwood Forest has been due to similar isolation brought about by very different causes. The migration of the Redwood Forest, beginning in the Eocene in the north, reached California by the close of the Miocene. It advanced along migration routes resembling tongues radiating from a central source. With the climatic changes that culminated in Pleistocene glaciation and subsequent aridity, these tongues were cut off from behind (at the close of the Miocene). Through isolation, the flora developed distinctive species generically related to species in other localities. For example, species of the genus Torreya occur in California, Florida, China, and Japan.

In conclusion we may state that in general endemism is the product of the isolation of floras. Along the California coast isolation has been accomplished in two distinct manners. That resulting in the endemic nature of the Monterey Forest appears to have been through diastrophism, while that bringing about the endemism in the Redwood Forest was largely the result of secular climatic change.

DISCOCYCLINA IN CALIFORNIA

BY HUBERT G. SCHENCK

(*Abstract*)

The orbitoidal foraminifer *Discocyclina* (*"Orthophragmina"*) occurs in Eocene sandstones and shales in the Coast ranges from Baja California to Marysville Buttes, in the Sacramento Valley, at latitude 39° 12′ north. The species *clarki*, of the Meganos Eocene near Coalinga, has recently been collected from the Domengine horizon of the Meganos in Simi Valley. The only decidedly umbonate representatives known in California are new species from the Tejon (?) sandstone near New Almaden, Santa Clara County. The flat, discoidal forms, commonly assigned to *D. clarki*, suggest that the Meganos should be correlated with the Claiborne Eocene of the Gulf Coastal region of the United States.

ADDITION TO THE MESOZOIC STRATIGRAPHY OF THE GREAT BASIN REGION

BY SIEMON MULLER

(*Abstract*)

During the summer of 1927 the writer visited the New York Canyon, in Volcano district, Pilot Mountains, Nevada, and collected material consisting, in order of their abundance, of pelecypods, cephalopods, gastropods, brachiopods, and corals. Identification of some of the forms reveals two distinct faunal assemblages. The stratigraphically upper fauna is unquestionably Liassic, probably lower Lias; the stratigraphically lower fauna probably represents still lower Lias or the very top of the Trias. No angular unconformity between the two horizons was observed.

SPECIES OF THE GENUS THYASIRA IN THE TERTIARY OF NORTH AMERICA

BY NELLIE M. TEGLAND

ECOLOGY OF THE MOLLUSKS OF THE BOWDEN FORMATION, JAMAICA

BY W. P. WOODRING

(*Abstract*)

The Bowden formation of Jamaica, of late middle Miocene age, carries a tropical fauna of about 600 species of mollusks. The presence of a few brackish-water genera (*Neritina*, *Mytilopsis*, and an oyster similar to the modern mangrove oyster) is attributed to unusual events, perhaps unusually heavy floods. Most of the Bowden mollusks lived on a bottom of sand and mixtures of mud, sand, and gravel. Rock-clingers, rock-borers, and mud-burrowers are rare or absent. Modern representatives of two genera (*Tralia* and *Planaxis*) live between high- and low-water marks or even above high-water mark. The sparsely represented rock-clingers (*Chlorostoma* and *Thais*) and some of the abundant sand-burrowers (*Oliva*, *Olivella*, and *Natica*) live in the intertidal zone and also below low-water mark. It is apparent that most of the Bowden mollusks represent the neritic zone. According to frequency graphs based on dredgings in the West Indian region, several genera

(*Seguenzia*, *Cocculina*, *Fissurisepta*, and *Tindaria*) indicate a probable depth of more than 100 fathoms. The relatively large number of pelagic mollusks and the large proportion of carnivores among the gastropods may have the same depth significance. It is suggested that the Bowden formation was deposited on a narrow coastal shelf, and that at times the sediments at the edge of the shelf and the shells buried in them were washed down the slope and came to rest at a greater depth, where they were mixed with autochthonous deep-water material. One genus of predaceous carnivores (*Nassarius*) seems to be responsible for most of the neatly bored holes seen in many shells.

GOSHEN FLORA

BY ETHEL I. SANBORN

(*Abstract*)

The Goshen flora is made up of about 40 species, a large number of which are referable to genera now living in the warmer parts of the world. The conditions under which this flora lived and its relation to other older Tertiary floras of western America are discussed.

TERTIARY MAMMALIAN FAUNA FROM THE KERN RIVER SERIES, CALIFORNIA

BY CHESTER STOCK, J. W. PATTERSON, AND E. L. FURLONG

(*Abstract*)

The Kern River deposits exposed on the east side of the southern San Joaquin Valley have furnished a mammalian fauna, including horses, rhinoceroses, peccaries, merycodonts, ground sloths, and other types. The fauna is discussed and a preliminary statement made concerning its relationship to known Tertiary mammalian assemblages of California.

MERYCHIPPUS ISONESUS (COXE) FROM THE LATER TERTIARY OF THE CROOKED RIVER REGION, OREGON

BY JOHN H. MAXSON

UPPER FAUNAL HORIZONS OF THE SAN FERNANDO GROUP IN LAS POSAS AND SOUTH MOUNTAIN DISTRICTS, VENTURA COUNTY, CALIFORNIA

BY EDWARD D. PRESSLER

(*Abstract*)

A brief discussion of the age relations and correlations of the faunal horizons found in the Upper Pico and Saugus formations of Las Posas and South Mountain districts. The correlations are made with the Ventura and San Pedro sections and they give evidence to show the presence of equivalents of the complete San Pedro section in the Ventura Basin.

REVISION OF THE TURRITELLAS OF THE VAQUEROS AND TEMBLOR MIOCENE OF CALIFORNIA

BY LIONEL W. WIEDEY

(*Abstract*)

Turritella variata Conrad appears to have been misidentified as a Temblor form by recent authors, whereas it apparently was originally collected from the Vaqueros formation, together with *Turritella inezana* Conrad. Moreover, the form erroneously referred to *variata* has never been found in the Vaqueros, but specimens from that formation closely agree with Conrad's description and figures of *variata*. A recently described species, *T. bosei* Hertlein and Jordan, of the Middle Eocene of Lower California, Mexico, is believed to be common in the Temblor of California. Some writers consider specimens of the Lower California species as variants of *T. ocoyana* Conrad. This revision necessitates the description of two new species and a variety.

FAUNA AND STRATIGRAPHY OF THE VAQUEROS FORMATION IN VENTURA AND SANTA BARBARA COUNTIES, CALIFORNIA

BY W. H. COREY

(*Abstract*)

The Vaqueros has a large fauna containing many new species, several of which are quite common. Some forms are apparently directly ancestral to Temblor species.

Field-work has also brought out some interesting facts concerning stratigraphic relationships of the Vaqueros formation in this region.

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SINCLAIR, WILLIAM J., Princeton University, Princeton, N. J.
SLOCOM, ARTHUR W., Walker Museum, University of Chicago, Chicago, Ill.
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WOODFORD, ALFRED O., Pomona College, Claremont, Calif.

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DR. CHRISTIAN POULSEN, Mineralogical Museum, Copenhagen, Denmark.
DR. ERIK A. STENSIÖ, Naturhistoriske Riksmuseeto, Stockholm, Sweden.
DR. ELSA WARBURG, University of Upsala, Upsala, Sweden.

NEW MEMBERS

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BECKWITH, FRANK A., Delta, Utah.
CARPENTER, FRANK MORTON, Bussey Institute, Forest Hills, Boston, Mass.
CLARK, ALEXANDER, 522 North Newlin Avenue, Whittier, California.
DILLÉ, GLENN SCOTT, Department of Geology, University of Iowa, Iowa City, Iowa.
DOTT, ROBERT H., Geological Department, Mid Continent Petroleum Corporation, Tulsa, Okla.
DRIVER, HERSCHEL L., 630 West Palm Drive, Glendale, Calif.
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FENTON, MRS. MILDRED ADAMS, Old Tech Building, University of Cincinnati, Cincinnati, Ohio.
GAZIN, CHARLES LEWIS, California Institute of Technology, Pasadena, Calif.
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HENBEST, LLOYD G., Peabody Museum, Yale University, New Haven, Conn.
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LAUDON, LOWELL R., Department of Geology, University of Iowa, Iowa City, Iowa.
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LUPER, RALPH L., California Institute of Technology, Pasadena, Calif.
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MILLER, ARTHUR K., 206 Geology Building, University of Missouri, Columbia, Mo.
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MULLER, SIEMON W., Department of Geology, Stanford University, Stanford, Calif.
OWEN, JOHN BRITTS, Clinton, Missouri.
ROWSER, EDWIN M., Department of Geology, University of Iowa, Iowa City, Iowa.
SANDIDGE, JOHN R., Princeton University, Princeton, N. J.
SMITH, ERNEST RICE, 309 Greenwood Avenue, Greencastle, Indiana.
STERNBERG, GEORGE F., Kansas State Teachers' College, Hays, Kansas.
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WARTHIN, ALDRED SCOTT, JR., Department of Geology, Columbia University, New York City.

WIEDEY, LIONEL W., Box 761, Palo Alto, Calif.

WILLIAMS, JAMES STEELE, 103 Geology Building, University of Missouri, Columbia, Missouri.

WILSON, CHARLES WILLIAM, JR., Graduate College, Princeton University, Princeton, N. J.

CORRESPONDENTS DECEASED

KOKEN, E. Died November 24, 1912.
NATHORST, DR. A. C. Died Jan. 20, 1921.
WOODWARD, DR. H. Died Sept. 6, 1921.

MEMBERS DECEASED

ARMSTRONG, EDWIN J. Died Jan. 21, 1925.
BARRELL, JOSEPH. Died May 4, 1919.
BILLINGS, W. R. Died March 1, 1920.
BOSTWICK, THOMAS A. Died April, 1923.
CALVIN, SAMUEL. Died April 17, 1911.
CLARK, WM. B. Died July 27, 1917.
CLARKE, JOHN M. Died May 29, 1925.
CROZEL, GEORGE. Died October, 1921.
DALL, W. H. Died March 27, 1927.
DEAN, BASHFORD. Died Dec. 6, 1928.
DERBY, ORVILLE A. Died Nov. 27, 1915.
EASTMAN, CHAS. R. Died Sept. 27, 1918.
FONTAINE, WM. M. Died April 30, 1913.
GILL, THEODORE N. Died Sept. 25, 1914.
GORDON, ROBERT H. Died May 10, 1910.
HAMLIN, HOMER. Died July, 1920.
HARPER, GEORGE W. Died Aug. 19, 1918.
HAWYER, J. C. Died May 15, 1914.
KNOWLTON, FRANK H. Died Nov. 21, 1926.
LAMBE, L. M. Died March 12, 1919.
LEE, WILLIS T. Died June 17, 1926.
LUSK, RALPH G. Died July 27, 1927.
LUTHER, D. D. Died Dec. 17, 1923.
LYON, VICTOR W. Died Aug. 17, 1919.
MARTIN, BRUCE. Died Dec. 23, 1919.
MATTHEW, GEO. F. Died April 17, 1923.
MOODY, W. L. Died Oct. 9, 1920.
PROSSER, C. S. Died Sept. 11, 1916.
SEELY, HENRY M. Died May 4, 1917.
SPRINGER, FRANK. Died Sept. 22, 1927.
TELLER, EDGAR E. Died July 19, 1923.
TWITCHELL, M. W. Died April 8, 1927.
VAN INGEN, GILBERT. Died July 7, 1925.
VOGDES, ANTHONY W. Died Feb. 8, 1923.
WALCOTT, CHARLES D. Died Feb. 9, 1927.
WARING, CHARLES A. Died Nov. 5, 1918.
WELLER, STUART. Died Aug. 5, 1927.
WILLIAMS, HENRY S. Died July 31, 1918.
WILLISTON, S. W. Died Aug. 30, 1918.
WILSON, HERRICK E. Died Jan. 24, 1925.
WHITTAKER, EDW. J. Died Sept. 14, 1924.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 40, PP. 273-280 MARCH 30, 1929

PROCEEDINGS OF THE NINTH ANNUAL MEETING OF THE MINERALOGICAL SOCIETY OF AMERICA, HELD AT NEW YORK CITY, DECEMBER 27 AND 28, 1928.

FRANK R. VAN HORN, *Secretary*

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SESSION OF THURSDAY AFTERNOON, DECEMBER 27

The Mineralogical Society of America held its ninth annual meeting at New York City as guest of Columbia University and the American Museum of Natural History, in conjunction with the Geological Society of America and the American Association for the Advancement of Science. At 2 p. m. the meeting was called to order by President Esper S. Larsen in the New York Academy Room of the American Museum of Natural History.

On motion of the Secretary, the reading of the minutes of the last annual meeting was dispensed with, in view of the fact that they have been printed on pages 105-117 of volume 13, number 3, of the *American Mineralogist.*

ELECTION OF OFFICERS AND FELLOWS

The Secretary announced that 152 ballots had unanimously been cast for the officers as nominated by the Council. For Fellows there was a unanimous vote of 69 ballots in the affirmative. All officers and Fellows as nominated were declared elected. The officers for 1929 are the following:

President, ARTHUR L. PARSONS
Toronto University, Toronto, Canada

Vice-President, EDWARD WIGGLESWORTH
Boston Society of Natural History, Boston, Mass.

Secretary, FRANK R. VAN HORN
Case School of Applied Science, Cleveland, Ohio

Treasurer, ALEXANDER H. PHILLIPS
Princeton University, Princeton, N. J.

Editor, WALTER F. HUNT
University of Michigan, Ann Arbor, Mich.

Councilor, 1929-1932, CLARENCE S. ROSS
United States Geological Survey, Washington, D. C.

The Fellows elected follow:

MR. MARTIN J. BUERGER, Massachusetts Institute of Technology, Cambridge, Massachusetts.
DR. JOHN W. GRUNER, University of Minnesota, Minneapolis, Minnesota.
DR. WALTER H. NEWHOUSE, Massachusetts Institute of Technology, Cambridge, Massachusetts.

The Secretary also announced that the Council, by virtue of authority given it by the constitution, had elected the following Honorary Life Fellows:

Prof. Friedrich J. Becke, University of Vienna, Austria.
Prof. Reinhard Brauns, University of Bonn, Germany.
Prof. W. C. Brögger, University of Oslö, Norway.
Prof. Friedrich Rinne, University of Leipzig, Germany.

REPORT OF THE SECRETARY

The Secretary reports that the roll of the Society now comprises 105 Fellows and 235 members in good standing. Three Fellows and 31

members have been dropped from the mailing list for non-payment of dues, leaving a net gain of 17 members for the year. In addition to the 340 Fellows and members, there are also 185 subscribers to the *American Mineralogist;* so that there are 525 paid copies of the journal of the Society mailed monthly, which is a net gain of 46 copies over the previous year.

No deaths have been reported during the year.

Forty-one Fellows, 51 members, and 16 guests registered at the meetings, making a total of 108, which exceeds all records of attendance.

There were 32 scientific papers presented at the meetings.

REPORT OF THE TREASURER

The Treasurer, A. H. Phillips, read his report, which showed a very favorable balance.

On motion, the report was accepted, ordered filed, and an Auditing Committee from non-members of the Council was appointed by the President. This committee, consisting of A. C. Hawkins, Harry Berman, and R. B. Gage, later reported to the Secretary that they had found the books of the Treasurer correct.

REPORT OF THE EDITOR

The Editor, W. F. Hunt, read his report, which, on motion, was accepted and ordered filed. During the year the *American Mineralogist* printed fifty-seven leading articles, totaling 526 pages. In addition, reports of proceedings of societies, abstracted accounts of new mineral species, book reviews, and notes and news brought the total amount of reading material up to 593 pages, which exceeds the previous high mark of last year by 153 pages. Subscriptions from libraries and educational institutions have continued to increase over the previous year.

REPORT OF THE COMMITTEE ON NOMENCLATURE AND CLASSIFICATION OF MINERALS

H. S. Washington, chairman, reported that the members living in Washington had had a meeting and requested that the committee be discharged. A motion to this effect was moved and carried.

W. T. Schaller moved that the President appoint a special committee of three, of whom not more than one has served on the Committee of Nomenclature, to reread all of the reports of that committee and abstract therefrom the most pertinent and important suggestions and submit them, in a condensed form, at the next meeting, with a request that

such a condensed report be printed in the *American Mineralogist.* This was carried, and the President appointed W. T. Schaller, C. S. Ross, and E. T. Wherry.

REPORT OF THE COMMITTEE ON PRESERVATION OF TYPE MINERALOGICAL MATERIAL

W. T. Schaller, chairman, read a report signed by all of the members of the committee, and moved that the committee be discharged, which was carried.

REPORT OF THE REPRESENTATIVE ON THE NATIONAL RESEARCH COUNCIL

W. T. Schaller gave a summary of various investigations being undertaken by subcommittees of the National Research Council.

NEW BUSINESS

T. L. Walker reported that he had heard nothing further about the establishment of a mineralogical section at the International Geological Congress at Pretoria, South Africa, on July 29, 1929.

PRESENTATION OF PAPERS

At 2:45 p. m., there being no further business and no memorial biographies, the presentation of scientific papers was taken up, according to program, as follows:

DETERMINATION OF THE CRYSTALLOGRAPHICAL CONSTANTS IN CRYSTALS OF THE TRICLINIC SYSTEM

BY A. L. PARSONS

CRYSTALLOGRAPHY OF THE QUARTZ PSEUDOMORPHS FROM PATERSON, NEW JERSEY

BY W. T. SCHALLER

SOME DEVICES AND MODELS FOR THE DEMONSTRATION OF SYMMETRY

BY H. P. WHITLOCK

STUDY OF CRYSTAL SYSTEMS

BY A. F. ROGERS

At 3:55 p. m. the Society adjourned to attend the joint session with the Geological Society.

Joint Session with the Geological Society of America, December 27

The Mineralogical Society of America held a joint session with the Geological Society of America at 4 p. m., Thursday, December 27, in the Duplex Assembly Room, second floor, School Service Building of the American Museum of Natural History, Vice-President A. C. Lane, of the Geological Society, presided. Dr. Esper S. Larsen, of the Mineralogical Society, delivered his presidential address, "The Temperature of Magmas," which will be published in the March number of the *American Mineralogist*. During the remainder of the afternoon papers of the Geological Society, of a mineralogical and petrographical nature were presented, with E. S. Larsen in the chair. The joint meeting adjourned at 6 p. m.

Session of Friday Morning, December 28

At 9:12 a. m., in the New York Academy Room of the Museum, President Larsen called the meeting to order. The reading of scientific papers then proceeded according to program.

PRESENTATION OF PAPERS

POLYSYNTHETIC TWINNING IN DOLOMITE

BY A. F. ROGERS

OPTICAL AND GEOMETRICAL CRYSTALLOGRAPHIC PROPERTIES OF THE BASIC AND NORMAL CUPRIC SULFATES AND TENORITE

BY E. POSNJAK AND GEORGE TUNELL

AN X-RAY STUDY OF THE DOMEYKITE GROUP

BY L. S. RAMSDELL

NOTES ON THE STRUCTURE OF BORACITE

BY J. W. GRUNER

PHOTO-LUMINESCENCE OF MINERALS

BY E. E. FAIRBANKS

MINERAL DETERMINATION IN CRUSHED FRAGMENTS WITH THE POLARIZING MICROSCOPE

BY A. F. ROGERS

INTERFACIAL TENSION OF CRYSTAL FACES

BY C. E. MILLER

ENDING OF CHEMICAL ADJECTIVES IN ISOMORPHOUS MINERALS

BY W. T. SCHALLER

THE LUDWIGITE GROUP

BY W. T. SCHALLER

NEW BASIC SULFATE AND TWO BORATES OF MAGNESIUM FROM STERLING HILL, AND FRANKLIN, NEW JERSEY

BY L. H. BAUER AND HARRY BERMAN

NEW BASIC CARBONATE OF MANGANESE AND ZINC FROM FRANKLIN, NEW JERSEY

BY L. H. BAUER AND HARRY BERMAN

CARMINITE FROM MEXICO AND COLORADO

BY W. F. FOSHAG

PERICLASE FROM CRESTMORE NEAR RIVERSIDE, CALIFORNIA

BY A. F. ROGERS

VIOLARITE, A RARE NICKEL MINERAL

BY M. N. SHORT AND E. V. SHANNON

QUANTITATIVE OPTICAL DETERMINATION OF POTASSIUM AND SODIUM CHLORIDE

BY C. B. SLAWSON

SERENDIBITE FROM WARREN COUNTY, NEW YORK

BY W. T. SCHALLER AND E. S. LARSEN

AN ILLINOIS RECORD COPPER ERRATIC

BY A. R. CROOK

NOTES ON THE APPEARANCE OF TOURMALINE IN SEDIMENTS

BY L. S. BROWN[1]

VOTE OF THANKS

The last paper, with the exception of those scheduled for the joint session of the afternoon, was finished at 12:59 p. m., after which it was moved that the thanks of the Society be extended to the local committee, and to the authorities of Columbia University and the American Museum of Natural History for their kindness and hospitality. This

[1] Introduced by F. R. Van Horn.

was seconded and unanimously adopted, after which the Society adjourned.

JOINT SESSION WITH THE SOCIETY OF ECONOMIC GEOLOGISTS, FRIDAY AFTERNOON, DECEMBER 28

The Mineralogical Society of America held a joint meeting with the Society of Economic Geologists at 2 p. m., Friday, December 28, in the New York Academy Room of the Museum. President E. S. Larsen called the meeting to order. Later in the afternoon President W. H. Emmons, of the Society of Economic Geologists, presided. The following papers were presented by members of the Mineralogical Society:

DIAMONDS AND DIAMOND MINES IN SOUTH AFRICA

BY G. L. ENGLISH

PARAGENETIC CLASSIFICATION OF THE MINERALS OF FRANKLIN, NEW JERSEY

BY CHARLES PALACHE

COMPARISON OF THE ORE DEPOSITS OF LANGBAN, SWEDEN, WITH THOSE OF FRANKLIN, NEW JERSEY

BY CHARLES PALACHE

THE PASSING OF THE FRENCH CREEK MINES

BY S. G. GORDON

REMARKS ON THE LLALLAGUA PHOSPHATES

BY S. G. GORDON

THE RUTHERFORD MINES, AMELIA COUNTY, VIRGINIA

BY A. A. PEGAU

NEW AND UNUSUAL NEW JERSEY MINERAL OCCURRENCES

BY A. C. HAWKINS

THE MANGANESE MINERALS OF A HYDROTHERMAL VEIN NEAR SPARTA, NORTH CAROLINA

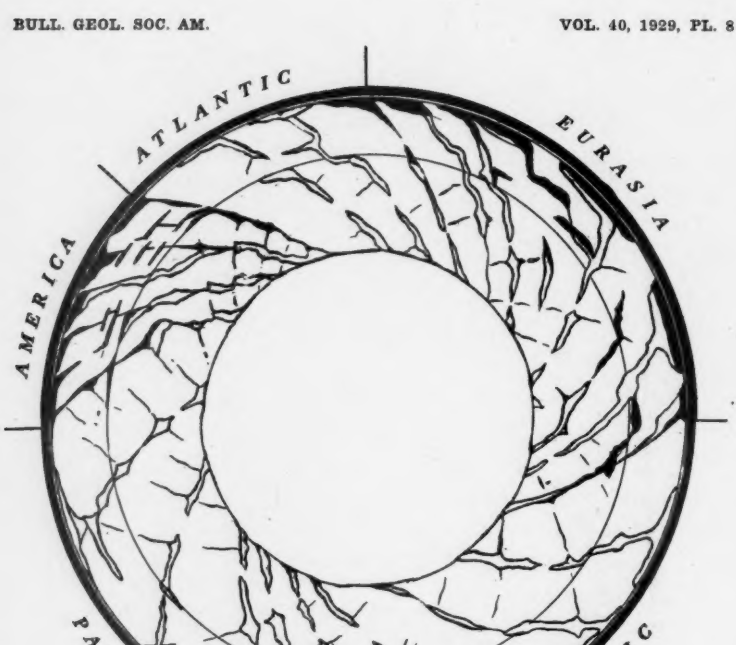
BY C. S. ROSE AND E. V. SHANNON

HALITE-ANHYDRITE INTERGROWTHS FROM TEXAS

BY W. T. SCHALLER

Four papers were also presented by members of the Society of Economic Geologists.

There being no further business before the Society, the joint session adjourned at 6 p. m. in order to attend the banquet of the Geological Society.



AUTOGENOUS DIKES

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 40, PP. 281-336, PL. 8-10 MARCH 30, 1929

CONTINENTAL GENESIS[1]

PRESIDENTIAL ADDRESS BY BAILEY WILLIS

(Read before the Society December 26, 1928)

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ADVANCED SUMMARY

This discussion of continental genesis is an attempt to formulate a consistent hypothesis of the origin and growth of continents.

[1] Manuscript received by the Secretary of the Society December 28, 1928.

A continent is defined as the outcrop of a mass which consists predominantly, but not exclusively, of granitic rocks in contradistinction to suboceanic masses of basaltic rocks. Therefore the genetic processes which result in continents are considered to be eruptive and are traced in the interior reactions of the earth's mass.

According to petrologic research, granitic rocks are differentiated from more basic magmas. Physical, chemical, and seismologic evidence indicates that the globe consists of an outer skin of diverse igneous rocks, a thick, solid shell of more basic rocks, and a dense, inelastic core, probably of iron. The inelastic condition of the last named is attributed to very high temperature. The most reasonable explanation of these conditions is found in the planetesimal origin of the globe, which is regarded as having had a cold core and as heating up internally.

Eruptions from the hot core or from the heated but solid shell are attributed to *strain-melting*—that is, to melting on shearing planes. The effect is to produce *autogenous dikes,* which are oriented in diagonal, not radial, positions and progress from deeper to higher levels. During their ascent they assimilate constituents of the rocks traversed and the resulting magma acquires a more or less acid constitution, the shell being regarded as heterogeneous.

A new term, stereosphere, is introduced for the inner shell of the envelope, 1200 miles thick.

Barrell's concept of an "asthenosphere" is accepted and is explained as the result of irregular and unequal conduction of heat from within outward. The active portion of the asthenosphere is assumed to be between 30 miles and 200 miles below the surface. It is locally characterized by rising temperature and local melting of the rock in such a manner as to produce blisters, to which the name *asthenolith* is given. The under surface of the skin, 30 miles more or less below the outer surface, is regarded as the upper limit of formation of asthenoliths, and also as a peculiarly favorable habitat for them.

An active asthenolith may result from eruptions from autogenous dikes or from melting in place in consequence of storage of heat. Its life comprises a period of growth by solution at melting temperature and a period of eruptive activity that ends in a state of chill. The characteristic magmatic changes in an asthenolith proceed from differentiation and result in acid and basic magmas that seek different levels. The degree of differentiation and the volumes of distinct magmas depend on the original composition derived from autogenous dikes and also on conditions within the asthenolith itself.

Eruptions from an asthenolith follow when it grows to such a diameter that the shearing stress around the margin exceeds the strength of the cover. Marginal outflows result in piling up on adjacent areas and in subsidence of the cover over the central region of the blister. The latter effect leads to the formation of tension cracks and eruption from the central part of the blister. Various surface features result from the different eruptions. Marginal discharges produce the suboceanic ridges or the crescent-shaped island arcs or the long batholiths of continental margins, according as the magmas are basaltic or intermediate or granitic. Centralized eruptions form large intrusive masses, which may take the character of submarine floors or that of continental nuclei, according to the composition of the magma.

Extinct and collapsed asthenoliths are regarded as forming the individual hollows that make up the broader ocean basins. Certain deeps, which are characterized by great seismic activity and beside which rise great mountain chains of intrusive or volcanic formation, are considered to represent active asthenoliths.

The continental nuclei are grouped in a peculiar manner in what is called the Land Hemisphere. An explanation of this fact is found in the original distribution of matter in the planetesimal state as it was shot from the sun, and also in the concentration of acid constituents in autogenous dikes and their differentiation in asthenoliths.

It is recognized that continental nuclei constitute the positive elements of the larger continents and lie surrounded by zones that have been called the negative elements. These conditions are believed to have resulted from the action of a horizontal compressive force which has welded the positive elements together, the negative elements representing the welds.

A source of the compressive force is found in the expansion of the covers of asthenoliths in consequence of intrusion and metamorphism contemporaneously with the progress of eruptive activity. The discussion of this subject, however, is left for another opportunity, under the title Metamorphic Orogeny. The bearing of the views here presented on such questions as the permanence of continents, isostasy, etcetera, is necessarily left for future discussion.

Definition

Continents are currently defined as large landmasses, or as elevated plateaus on the earth's surface, or as masses of lighter rocks riding high in isostatic equilibrium with masses of denser rocks. The last of these

three definitions is the most significant. It recognizes established differences of specific gravity and through them interprets the facts that lie back of the other two definitions. Continents are large land areas and are elevated plateaus, because they consist of lighter rocks. Per contra, oceanic areas lie at a relatively low level and are submerged because they are underlain by heavier rocks.

The terms *lighter* and *heavier* may, for the purposes of this paper, be translated into the general names of two families of igneous rocks, namely, the *granite* family and the *basalt* family. It is understood that the granite family comprises the rock types from aplite to diorite, whereas the basalt family includes all those ranging from diorite or gabbro to peridotite. The former constitutes the *acid* (siliceous) group, the latter the *basic* (ferromagnesian) group. The same distinction is expressed by the terms *sial* and *sima,* introduced by Suess to designate respectively the group of rocks that makes up the continents (sial) and all other portions of the earth's crust (sima), extending under the continents and ocean beds alike.

On the basis of these facts and definitions we may define *a continent* as *the outcrop of a mass which consists predominantly, but not exclusively, of granitic rocks, in contradistinction to suboceanic masses of basaltic rocks.*

The definition at once suggests the line of investigation which should lead to a reasonable hypothesis of genesis. All the rocks involved are igneous, for we may neglect the thin and tattered mantle of sediments. We may therefore postulate any process that leads to the aggregation of large bodies of igneous rock of distinctive composition, and we shall undoubtedly find the best clues in the work of the petrologists. Experimental studies of the physical characteristics and mutual reactions of the acid and basic silicates on each other in passing from the solid to the liquid state, and *vice versa,* throw a penetrating light on the evolution of rocks. Even so, the origin of the substances, the arrangement of minerals in the globe, the physical environment of the reactions, the resulting structure of the earth's crust, and the geologic changes involved in continental histories present difficult problems. The path of research leading to a concept of continental genesis is no broad highway. It branches into many byways and into numerous blind alleys. In framing the following theory I present the view which is in sight after treading the trail for some two score years in stimulating association with fellow-students. The morning mists still hang over it. When they are dispelled it may look differently.

Hypothesis of Continental Genesis

Continents are formed by the aggregation of large intrusions of granitic rocks which have been differentiated from more basic magmas in consequence of repeated melting and crystallization during their ascent from great depths.

The conditions of melting and recrystallization many times over are to be sought in changes of temperature, of confining pressure, and of differential strain in the heterogeneous solid earth.

The peculiar grouping of continents in the northern hemisphere is attributed to a distribution of lighter and denser minerals inherited from the planetesimal stages of terrestrial growth.

The general forms of the continents have been determined in part by rotational strains. The details of continental structure and outline result from grouping of the constituent bodies according to their specific gravities, magnitudes, forms, and relative positions.

The comparatively elevated positions assumed by the continents are equilibrium levels attained by the lighter intrusions, originally, not secondarily. The solidified mass tends isostatically to maintain its elevation, and in consequence of horizontal compression it is subject to deformation by foliation and shearing, which produce local uplifts and also result in depressions.

Whatever originality there may be in this hypothesis lies in the organization of the ideas to make them work, rather than in the novelty of the ideas themselves. Many of the postulates are accepted doctrine; others are taken from the working concepts of fellow-geologists: G. K. Gilbert, T. C. Chamberlin, A. L. Day, N. L. Bowen, F. D. Adams, L. H. Adams, H. S. Washington, R. A. Daly, and others. In the discussion I have tried to give due credit, whether for that which I have found in their writings or for ideas more or less consciously acquired in discussion.

Before discussing this hypothesis of continental genesis, it is desirable to sketch its predecessors, some of which may still dispute with it the gage of truth. Those who prefer not to break the thread of thought should turn to the heading, Current Concepts, page 289.

Historical Sketch

Some two centuries ago Buffon, according to Geikie,[2] imagined that the earth had passed through a molten state and in cooling had produced ridges and hollows. In time the waters condensed on the surface, which they completely covered, as is demonstrated by the widespread occur-

[2] Sir Archibald Geikie: Founders of geology, 1897, pp. 8-12.

rences of fossil shells. Cracks appeared, however, and a portion of the waters sank into the cavernous interior, leaving the dry lands or continents as they now exist. Extraordinary as were the clear-sighted intelligence and powerful imagination of the great cosmogonist, who not only conceived a history of changes on the earth, but also traced the planets back to their planet, the sun, he nevertheless was without the light of geologic knowledge and his concepts suggest grotesque forms glimpsed before dawn. Yet Suess, Haug, and others of the modern school who regard the collapse of hypothetical lands and continents as a condition precedent to the formation of mediterranea and ocean basins also see strange things, even in the morning light.

The Laplacian hypothesis of earth genesis gave the concept of a once molten earth a logical origin and fixed it firmly as a basic postulate in the geologic speculations of the nineteenth century. Dana deduced the appropriate effects of contraction during solidification and framed his hypothesis of the origin of continents and mountain ranges accordingly. In 1846, in discussing the volcanic activity of the moon, he wrote.[3]

"The moon gives us hints on another topic of great interest, relating to the distribution of land and water on our globe. We have mentioned that there is a large area covering nearly one-third of the hemisphere facing the earth, which is mostly free from volcanos, while on other parts the craters are closely crowded together. We may therefore reasonably infer that over this naked portion the surface first became solid and has therefore cooled the longest and to the greatest depth. Consequently the contraction from cooling which was going on would take place most rapidly over the thinner and more yielding volcanic portion; and unless the ejections made up the difference this part would become somewhat depressed. . . . Now, on our own globe the continents have, to a very great extent, been long free from volcanic action. . . . It is therefore a just conclusion that the areas of the surface constituting the continents were first free from eruptive fires. These portions cooled first and consequently the contraction in progress affected most the other parts. The great depressions occupied by the oceans thus began, and for a long period afterward continued, deepening by slow, though it may have been unequal, progress."

In 1873 Dana stated his mature views on the subject of the origin of continents as follows:[4]

"1. The defining of the continental and oceanic areas began with the commencement of the earth's solidification at the surface, as proved by the system of progress afterward.

"2. The continental areas are the areas of least contraction, and the oceanic basins those of greatest, the former having earliest had a solid crust.

[3] American Journal of Science, 2d series, vol. ii, 1846, p. 352.
[4] American Journal of Science, 3d series, vol. v, 1873, p. 423.

After the continental part was thus stiffened and rendered comparatively unyielding, the oceanic part went on cooling, solidifying, and contracting throughout; consequently it become depressed, with the sides of the depression somewhat abrupt. The formation of the oceanic basins and continental areas was thus due to unequal radial contraction."

Joseph Le Conte in 1859 considered an hypothesis of the formation of continents and sea bottoms by the unequal thickening of a floating crust, but he became dissatisfied with it and in 1872 referred to it as too hypothetical. He had become convinced by the argument of Hopkins, based on the facts of precession and nutation, that the earth "behaves like a perfectly rigid solid and not at all like a liquid or partly liquid body." This view he found confirmed by the researches of Thompson (Lord Kelvin) on the resistance of the earth to tidal stresses. He nevertheless looked on unequal contraction as the cause of irregularity of the surface of the earth and attributed the inequality to differences of conductivity in a heterogeneous globe. He says:[5]

"Suppose a solid earth of oblate spheroid form and even surface, covered with a universal ocean and cooling by radiation. If the material were homogeneous and therefore of equal conductivity along every radius, then the cooling and the consequent contraction along each radius would be equal, and, so far as this cause is concerned, the earth, though becoming smaller, would maintain its symmetry of form and its universal ocean. But such homogeneousness could not be expected, nor does it exist. In a heterogeneous earth thus cooling, areas of greater conductivity would cool more rapidly and therefore contract more rapidly in a radial direction. These more conductive areas with shorter radii would form the sea bottoms, while the less conductive and therefore less radially contracted portions would become land surfaces. . . .

"The law of fluid equilibrium requires that in the preexisting fluid condition, and therefore also when the earth first become solid, the quantity of matter along each radius was nearly or quite equal. This equality would not be affected by the subsequent unequal contraction. It seems probable, therefore, that the same equality still exists, and that, therefore, the matter along the shorter oceanic radii is denser than along the longer continental radii."

Le Conte thus recognized the condition of distribution of density which later became the basis of the theory of isostasy.

The views of Dana and Le Conte, presented above and discussed at length in the papers referred to, are thoroughly representative of the condition of theory in America and Europe at the time of their publication. The two American geologists led in the development of ideas on the major problem of continental genesis. They also discussed at length

[5] A theory of the formation of the great features of the earth. American Journal of Science, 3d series, vol. iv, 1872, p. 352.

the related problem of mountain-building and attributed the elevation of mountain ranges to a common cause, lateral compression and crushing, but argued that the mechanism must be that which would follow from the liquid or solid condition of the globe, each according to his basic conception of the state of cooling attained.

Mountain ranges and deep troughs are phenomena which have both been discussed as being intimately related to the genesis of continents. James Hall first called attention to the troughs which are now generally known by the name given them by Dana, *geosyncline*. The characteristic habit of geosynclines is to subside, accumulate a great thickness of strata, and rise in a folded mountain range. Hall, in 1859, published a discursive account of his views on the causes of the formation of geosynclines. His leading thought is expressed as follows:[6]

"At this point of our inquiry several questions of importance present themselves: First, what has been the cause of this folding and plication of the strata; secondly, having been thus folded and plicated, what influence has this action exerted on the elevation of the parts, or of the whole; and, thirdly, what effects are due to the metamorphism which accompanies this mountain chain?

"It has been long since shown that the removal of large quantities of sediment from one part of the earth's crust and its transportation and deposition in another may not only produce oscillations, but that chemical and dynamical action are the necessary consequences of large accumulations of sedimentary matter over certain areas."

Hall attributed the subsidence of the bottom of a geosynclinal trough to the accumulation of the sediments and in so far anticipated modern theories of isostasy,[7] but his ideas of possible causes of folding and uplift were vague and were criticized by Dana as "a theory of the origin of the mountains with the origin of the mountains left out." There would be no occasion to refer to Hall's discussion of geosynclines in connection with theories of continental genesis if the facts to which he first called attention had not been discussed half a century later as criteria by which to define the boundaries of continents and to demonstrate the former existence of now vanished lands. In 1907 Haug[8] wrote:

"Geosynclines are always situated between two continents and constitute essentially mobile zones, comprised between two relatively stable masses."

Applying this definition to the outlines of the actual continents and to the Tethys, he traces a plan of geosynclines that requires the former ex-

[6] Paleontology of New York, vol. iii, part 1, 1855-59, p. 69.
[7] William Bowie: Isostasy, 1927, pp. 267 et seq.
[8] Emile Haug: Traité de Geologie, vol. 1, 1907, pp. 163-166.

istence of continental masses in the north and south Atlantic, in the Indian, and in the Pacific basins, up to the close of the Mesozoic era. Where deep ocean basins now lie depressed, there must have been lands to constitute the boundaries of the geosynclines! Where the waters were when all the surface of the earth except narrow canals was land does not appear; nor how the varied and abundant marine life of the Mesozoic survived in its narrow habitat; nor how the rains were maintained; nor how the luxuriant plant life flourished if they were absent. It is a view seriously put forward which nevertheless enlivens the discussion.

To indicate the background of Haug's idea it is necessary to quote from Suess:[9]

> "Subsidence or collapse has left its traces everywhere. Sometimes it produces great troughs in the midst of tablelands, sometimes subsidence of plateaux along peripheral lines; at others cauldron-shaped insinkings on the inner border of folded mountains; at others again the subsidence of folded mountains along longitudinal or transverse fractures. The diversity in character of the effects produced by downward movement is extraordinary and their magnitude extremely great. It is to subsidence and collapse that the mediterranean seas and the largest oceans owe their origin and enlargement."

Thus, in the twentieth century, the views of Buffon appear.

Current Concepts

American research into the larger problems of geophysics, as the subjects of continental growth and mountain-building came to be called, received fresh stimulus from the discussions by Gilbert, Dutton, and Powell during the eighteen-eighties. To a young geologist, educated in the belief that Dana was the final authority on such questions, it was a wholesome shock to hear Dutton argue that contraction was hopelessly incompetent to produce the degree of folding already demonstrated. Gilbert's philosophic indifference to the desire for immediate conclusions suggested restraint of opinion, and Gilbert's encouragement directed the work of research into the mechanics of Appalachian structure, a field in which it had seemed that the Rogers brothers had "threshed out all the wheat and left only chaff."

Isostasy, the hypothesis of balance between the continental masses and the suboceanic bodies, which was first suggested by Babbage and Herschel and was glimpsed by Le Conte, was the central concept discussed. It was accepted in principle, but from the beginning there were those differences of opinion as to the degree of balance which still divide isostasists.

[9] Edouard Suess: Das Antlitz der Erde, 2te Aus., 1892, B. I. S. 777-78. English translation, vol. i, 1904, pp. 603-04.

Dutton reasoned that the evidences of sedimentation demonstrate a relation of cause and effect between the weighting of sediments and the subsidence of the loaded areas. Gilbert leaned reservedly to a less sensitive, more rigid condition of the earth's crust.

We need here only to refer to the classic research by Gilbert into the rigidity of the earth, as illustrated by the deformation of the Bonneville basin, or to Barrell's exhaustive studies of the strength of the earth's crust, or to the remarkable contributions to the theory of measurements of gravitative equilibrium by the geodesists Hayford and Bowie. These contributions are familiar to all students of geophysics. Unfortunately, they do not determine the degree of isostatic compensation in contrast to the amount of rigid support.

In the meantime a new branch of investigation, petrography, grew up. Initiated by Sorby in 1850, elaborated by Zirkel, Rosenbusch, Fouqué, and Michel-Levy, it has been developed into the science of petrology by Cross, Daly, and Iddings among geologists, and by the petrologists Bowen, Vogt, Harker, Washington, and others. By means of experimental physical chemistry it throws an intense and penetrating gleam of light into the depths of the earth and suggests explanations of chemical activity among minerals which are most significant in the study of the origin of the granitic and basaltic masses that enter into our problem.

Seismology, the science of earthquake knowledge, has also during the past few decades developed from the stage of observation into that of interpretation, and lays a sensitive finger on the elastic waves in their passage through the different shells of the globe. It enables the mathematical physicist to determine the state of elasticity, rigidity, and density from the surface down to a depth of 2,860 kilometers (1,777 miles), and to demonstrate that this shell, nearly half the radius in thickness, is elastic throughout. Within it is a core with a radius of 3,470 kilometers (2,156 miles), which apparently does not transmit transverse elastic waves as solids do and may be described as inelastic and nonsolid.[10]

The state of matter of the core, whether liquid or gaseous, is indeterminable, since we have no experience of matter at the very high temperature and pressure existing at that depth in the earth. But, being relatively inelastic, it may be regarded provisionally as a viscous liquid, to convey the idea that it lacks the crystalline structure and

[10] J. B. Macelwane, S. J.: The interior of the earth Bull. Seis. Soc. of Amer., vol. 14, 1924, pp. 81-87, and personal communication.

elastic properties of the solid envelope. The core is, however, certainly not mobile. While its resistance to distortion is probably lower than that of the envelope, it must be very great.

The fact that the core and the envelope react differently to stresses such as tidal distortion has a place in our discussion as a condition which may concentrate strain and produce melting.

Genesis of the Core and Envelope

Had this demonstration of the existence of an inelastic core within a thick, solid envelope been offered thirty years ago, it might well have been regarded as conclusive confirmation of the once molten condition of the entire globe. The envelope would be the cool crust and the core the still molten heart. From this point of view the earth must be regarded as a cooling system, running down. It is still so regarded by many scientists.

An alternative concept springs from the idea that the globe grew up as a solid sphere, but has been melted at the center by the conversion into heat of potential energy derived from compression. So long as that process has not reached an equilibrium, we would be dealing with a heating system instead of a cooling one. The earth would be a heat engine.

The alternative bears on the perpetuation of geologic activities. If the earth has cooled down to its present state, the greater energy of earlier stages should then have produced at the surface more vigorous effects of continental development and mountain growth. Man should live on a relatively featureless earth. The contrary is true. Thus the more promising line of research for an inquiry dealing with the evolution of continents follows from the suggestion of a heating earth.

The idea that the earth has grown up as a solid globe is a conclusion of the Planetesimal theory of its origin.[11] The opposed view, that it must have passed through a molten stage, followed from the Laplacian hypothesis, which is now discarded; but it also follows from the Tidal Disruptive theory of Jeffreys,[12] which is currently favored, especially by mathematical physicists.

In order that the reader may have these basic theories before him, they are summarized in the following parallel. The original works should be consulted for fuller information.

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[11] T. C. Chamberlin: The two solar families. Chicago University Press, 1928.

[12] Harold Jeffreys: The earth, its origin, history, and physical constitution. 1924. pp. 1-35.

ORIGIN OF THE EARTH: PARALLEL STUDY OF TWO THEORIES

THE PLANETESIMAL (Chamberlin and Moulton)	*THE TIDAL DISRUPTIVE* (Jeffreys' modification of Jeans theory)
Initial Postulates	
For many years these two students had examined the distribution of masses and the dynamical endowments of the planetary system, and they used these data as the basis on which to frame a theory of the earth's origin. Using the method of multiple hypotheses, they had tested and disproved all theories of gaseous or meteoritic origin. The Planetesimal theory was the logical result of further search for alternative modes of origin.	These two investigators approach the subject of planetary genesis as astronomers, following out the evolution of a star, our sun. Tidal disruption of the sun, previously postulated by Chamberlin as an essential element of the Planetesimal theory, is adopted and elevated to the position of a first and only cause of the birth of the planets.
The sun at the time of the birth of the planets is assumed to have been a gaseous star, very similar to the actual sun, a dwarf star.	The primitive sun is assumed to have been a gaseous star in the giant stage, strongly condensed toward the center, not more than 21 million kilometers in radius.
The sun is assumed to have been endowed with great internal eruptive and propulsatory energy then as now.	Sun's activity not regarded as an important factor.
A passing star stimulated the eruptivity of the sun and caused four double eruptions from the eruptive belts.	A passing star created disruptive tidal effects through its gravitative attraction only.
The star passed at a high speed in an open hyperbolic orbit. Assumptions regarding the star are not rigorously limited, Moulton having by a mathematical study of	The star is assumed to have been much more massive than the sun. The possibility of reciprocal tidal action of the sun on the star is disregarded.

48 cases shown that any one of a number of working subhypotheses might give rise to matter circulating about the sun at planetary distances.

The encounter of the sun and star is described as neither slow nor transitory, but of an intermediate type.

Postulates regarding the planetary Substance

The material substance of the planetary system was originally a part of the gaseous sun.

The material substance of the planetary system was originally a part of the gaseous sun.

This substance was endowed by the passing star with a large proportion of the total great momentum now possessed by the planets, in contrast to the relatively small momentum of the massive sun.

The contrasts of masses of the sun and planets and of their momenta are discussed and used as they had been by the authors of the Planetesimal theory.

While still in the sun, the substance that was to become a planet shared in the turbulent state of the sun and received additional energy in the process of expulsion by the tidal effects.

The internal energy of the gas in the sun is not mentioned and the discussion of conditions after disruption does not take account of it.

"Earth bolt shot from the sun."

"Filament drawn out or shot out from the sun."

The planetary bolt is assumed to have been endowed with cyclonic rotational motion and other activities, like a rolling cloud.

The ejection of the filament is discussed as having been encouraged by "fluid pressure."

Emphasis is laid on the dispersive effects produced by the kinetic energy of the gas, the cyclonic and evortical activities of the bolt, and the release of pressure in passing from the body of the sun into the almost absolute vacuum of space.

Dispersive activities of the filament are assigned a minor rôle. It is assumed to retain its form under its own gravitational attraction.

The form assumed by the substance of any planetary bolt is that of a swarm following a broad orbit around the sun. The original cy-

The form of the whole filament is described as that of a long protuberance toward the star, which, in case of steady joint influence of

clonic and evortical motions persist in the swarm, though modified by the change in environment. There is a strong tendency to dispersion at the outer end of the bolt, where lighter molecules prevail, and less tendency at the rear end, where heavier molecules predominate.

the sun and star, would resemble a "boomerang," somewhat thicker in the middle than at the ends, but would condense toward any center of slight distortion, causing a local increase of mass per unit of length.

After leaving the Sun

The rapid expansion of the mass and the radiation of energy into space induced immediate cooling and solidification, forming solid atoms, molecules, or accretions. All of these may be planetesimals if they behave dynamically like planets. The essential thing is that the swarm took on an orbital organization in contrast to the gaseous organization. In that dynamical change lay its chance to assemble and form a planet.

When the length of the filament reached a value calculated as a function of the velocity of sound in the gas, the density, and the gravitational constant, it detached itself and began its existence as a separate body, unless it fell back into the sun. It separated into segments which, if they continued their separate existence, became independent planets.

The formation of a liquid or solid core was the beginning of aggregation of the swarm of planetesimals. It could have occurred only among plantesimals having concurrent orbits that were not strictly parallel and in which speeds were not the same. If revolving in these relations, plantesimals would come together by overtake collisions and side-swipes. In these mild encounters the more elastic might rebound and suffer a partition of energy; the more brittle might break; but the heavier silicates and tough metallic constituents would coalesce. When

The length and thickness of a segment at rupture would be comparable, and it would assume a nearly spherical form without alteration of the order of magnitude of its density. It would thus form a gaseous sphere.

Since gas tends to spread into a surrounding vacuum, the gaseous planet must have had at least a minimum mass in order that its gravitative attraction might hold its substance and prevent dispersion. The minimum radius of the primitive planet is calculated to have been about one-sixtieth of that of the primitive sun.

erupted from the sun the material of the swarm was already less dense at the outer end of the bolt and denser at the inner end. Thus density conditions favored the assemblage of a core near the inner end where the inrolling motion was also favorable.

The growth of any core depended on the amount and density of the material moving in concurrent orbits and later on its sphere of control. The latter was determined by competition with other planetary cores and with the sun.

The core thus gradually drew to itself the available planetesimals within its control and became the planet without having passed through a liquid state at any stage.

The gaseous body of a great planet condensed by radiation, liquid drops forming on the outside and falling inward under gravity. They would collect with the densest at the center. Liquefaction would set in and proceed until complete. The smaller planets, from twice the mass of the earth down, would behave in part as the larger ones do, but because of insufficient gravity would probably lose a large part of their mass.

All planets must pass through a completely liquid state. Solidification would result from the formation of a crust, which would break up and sink in the molten globe, gathering at the center. The solid mass would increase in proportion to the magma until the whole became a honeycombed solid with liquid pockets.

The parallel between the Planetesimal and Tidal theories brings out the fact that they have in common only the assumption of a tidal effect produced by a passing star. This concept was first worked out by Chamberlin and Moulton and was adopted by Jeffreys, who built on it an entirely different hypothetical development.

The initial difference lies in the assumption regarding the condition of the sun at the date of birth of the planets. Chamberlin bases his deduction on the actual conditions. He assumes that the sun was then as now, a vigorously eruptive dwarf star, and attributes the expulsion of the planetary substance primarily to that eruptivity, secondarily to the stimulating tidal attraction of the passing star.

Jeffreys says:

"It seems unlikely on several grounds that a dwarf star could have been as heterogeneous as the present (Tidal) theory requires. Thus the origin of the planet must have happened while the sum was in the giant stage. It was then a gaseous star."

It is difficult to follow this statement, since the actual sun, a dwarf star, is known to be sufficiently heterogeneous to contain the principal

elements found in the planets. The important conclusion that the sun *must* have been in the giant stage is thus left without supporting reason. We might admit that it may have been, but the coincidence of the passage of the star with the particular instant when the sun had a certain radius, density, and temperature, required by an arbitrarily selected theory, would be quite fortuitous. The habit of thought of the mathematician is illustrated by Jeffrey's postulate that the time *"since the solidification of the earth is 1.6 x 10^9 years or 5 x 10^{16} seconds"* (page 85). What does it mean to convert the incomprehensible era of one and six-tenths billion years into 5 quadrillion seconds? What is the concept of solidification that permits its conclusion to be dated to a second?

This is a characteristic example of the difference in methods pursued by the two investigators. Chamberlin reasons from the known facts; Jeffreys seeks a condition that fits his hypothesis. This is an intellectual difference, and neither type of mind is likely to be able to follow the arguments of the other with confidence.

Either the Planetesimal or the Tidal theory of the origin of the earth would serve as a basis for deductions regarding continental genesis, but careful study indicates that Jeffreys's brilliant mathematical abstractions relate to ideal conditions, whereas Chamberlin's reasoning keeps constantly in touch with reality. To a geologist accustomed to keep his feet on the ground, the latter seems the surer guide to the truth.

A grave objection to the Tidal Disruption theory of Jeffreys, as to any other theory which requires solidification of a molten globe, is the very limited endowment of energy left to the earth in its primitive stage. The potential energy of infall of its substance, together with the latent and sensible heat of the magma, is all expended. The honeycombed solid would be very inadequately supplied to continue its activity throughout a billion years or so, as the earth has done. The planetesimal earth, on the other hand, would retain the potential energy of infall as internal heat and would be so conditioned that it could continue active down to the very present, as is the case with our globe.

Critical Facts and Probabilities

In attempting to trace the origin and development of continents we have to explain the occurrence of very large masses of granitic rocks which have been melted and intruded into the outer crust of the earth. The finger of inquiry points downward toward the interior, and we may here recall the fact that the central portion is an inelastic core, and that the envelope consists of elastic igneous rocks. The whole has certainly been melted, but successive melting and remelting of minute fractions

would bring about the present state of things quite as effectively as if it had all been molten at once, fractional melting has been the actual process. The heat generated by compression within must have escaped toward the surface in such a manner and under such conditions as to cause local melting. The converse, local cooling and solidification, is of course implied. We are thus led to consider the conditions under which heat may have been transferred from the core to the envelope.

Heat must escape from the overheated core by conduction and may also have migrated with molten filaments or masses as their sensible and latent heat.

We proceed to consider the conditions of conduction.

The rates of conduction under pressures and at temperatures within our experience have been determined for some minerals and rocks, but the absolute values are not significant in this study, since they would be greatly modified by the excessive conditions existing deep within the earth. Relative values only need to be considered.

Experimental studies indicate that acid rocks conduct heat better than do basic rocks. On the assumption, which though true in general is not necessarily exact in detail, that the rock of the envelope is more basic at greater depths, this relation implies that the rate of conduction is speeded up from within outward. If this were so, heat would be carried off as fast as supplied and no increment of temperature would anywhere be possible. Considering that the energy proceeding from the relatively small volume of the core would be dispersed in the larger volume of the envelope, the temperature would everywhere and at all times have been low. This inference is contradicted by the eruptive and metamorphic heat effects characteristic of all geologic ages. We are constrained by the facts of dynamic history to seek conditions favorable to increments of temperature in the envelope, though they may probably be local and not permanent.

Radioactivity is a source of heat which is of great potency but it is especially concentrated in an outer shell of the earth. It may be adequate to explain some superficial phenomena, but we can not well attribute melting at greater depths in any notable degree to that cause.

According to the generally accepted explanation of conduction of heat, the rate of a conduction is increased by pressure. Pressure in the earth augments inward to a degree which closes all pores at shallow depths and reduces molecular interspaces progressively at greater depths. The molecular vibrations which are expressed as heat should be transmitted more rapidly through the more compressed rock.

Bridgman's experiments [13] on the relative conductivity of metals under high pressure confirm this inference in two cases, but show the opposite in nine others. There are, however, differences in molecular organization between metals and silicates which tend to invalidate any comparison. Similar experiments on minerals would be necessary to check any general deduction, and those are lacking.

We thus have two contradictory influences which may affect the rate of conduction from within outward. If augmented pressure increases the conductivity of silicates faster than that conductivity decreases with change toward more basic constitution, then heat is conducted more rapidly at greater depths and less rapidly at shallower depths. This possibility was first suggested by Chamberlin,[14] who showed that an outer shell must, under those conditions, have a rising temperature.

If the earth were composed of spherical shells, each one of which was homogeneous in itself, the distribution of heat by conduction would, under the above conditions, be expressed by a gradient which would rise everywhere similarly in approaching the outer surface; but if horizontal heterogeneity exists, the plus or minus effect of changes of constitution and of pressure must result in notable differences of temperature at the same horizon. An ideal normal temperature might be reached and would be maintained in more acid rock overlying more basic, whereas, if the acid rock were underneath, the temperature would rise beneath the more basic layer. Other things being equal, the temperature represented by any isogeotherm will more nearly approach the outer surface of the earth the greater the proportion of acid rocks in any radial column.

Since the superficial continental masses consist predominantly of acid rocks, it follows from these considerations that there can be no accumulation of heat beneath them in the normal development of temperatures. This conclusion is thought to have a bearing on the apparent absence under the continents of the bodies which are later to be described as asthenoliths.

A heterogeneous structure in the earth would be a natural result of any mode of accumulation of so large a mass. According to the Planetesimal hypothesis, a heterogeneous arrangement originated in the sun and is perpetuated superficially in the division of the earth into the land and water hemispheres. It would also extend to the depths. If it be assumed that the earth was once molten, it would be impossible

[13] W. P. Bridgman: Proc. Amer. Acad. of Science, vol. 57, 1922, p. 75.

[14] T. C. Chamberlin: Manual of Geology, 1909, p. 565, hyp. 7.

to exclude differentiation of the igneous rock as the mass cooled, and the segregated masses would certainly give rise to heterogeneity.

The distribution of heat by conductivity must therefore result in more or less irregular isogeothermal surfaces. Conductivity of heat by rocks is, however, at best exceedingly slow and is not credited by physicists with an efficiency adequate to have carried away more than a small proportion of the energy developed by self-compression of the earth. Other means of heat transfer must be considered and are to be found in the rise of heated masses from the interior.

MELTING

Energy is required to raise the temperature of any substance to the melting point at an actual confining pressure, and beyond that amount to supply the latent heat of fusion. The required increase of temperature may be very slight, but the energy which is transformed into latent heat is a definite and notable amount. It breaks up the crystalline structure of the molecules and endows the atoms with the mobility of the viscous magma. There can be no melting unless this energy is supplied.

Geologists are so familiar with manifestations of energy in the earth, throughout the long past and in the actual present, without apparent diminution, that they assume an inexhaustible store. Physicists, reasoning that processes must run down unless wound up, anticipate exhaustion and inactivity. In a problem like the present one they inquire concerning the source of energy required to promote melting when melting is assumed. Here we are again thrown back on the question of a once molten globe in contrast to an earth that has grown up as a solid body.

In a globe cooling from a molten state any residual energy of the still molten masses would diminish as solidification progressed. If the envelope thickened it would ever more efficiently restrain the effect of the internal energy on the surface and the globe should gradually pass into a stage of external quiet. It has not yet done so, although seven-eighths of its mass is solid.

On the other hand, if the earth has grown slowly by the infall of planetesimals, the internal compressive stress has been constantly augmented and the energy available for conversion into heat has grown correspondingly. It may be that the rate of infall has declined and that growth may have practically ceased, but it does not follow that compression is finished. That would be the condition only in case the globe were completely solidified. Since we recognize an inelastic core which

is presumably molten, the factors that determine the actual state of the interior are the energy of compression, on the one hand, and on the other the heat used up in melting an inner shell of the envelope and the heat which escapes through the envelope.

This offers us the somewhat unexpected suggestion that the envelope is actually growing thinner and would reach a minimum thickness when the solid shell would break up and sink. Further cooling would ultimately result in complete solidification of the globe. We have no means of knowing at what point in this hypothetical cycle of changes the earth stands. Any change is certainly very gradual, for the geologic record of all ages since the Precambrian fails to show any evidence of variation in surface conditions.

The problem of melting or solidification in the whole globe is, however, of less significance in our discussion than that of local melting. Geologic phenomena require localized energy, periodically intensified and exhausted, and as often renewed with short cycles imposed on longer ones. There is some cause or group of causes in the mechanism which acts to introduce an irregular and local rhythm in the distribution of energy.

In seeking for this cause we turn to the fact that strain is a condition which effectively promotes local melting of a crystalline substance, provided the temperature be already high. Van Hise [15] emphasized the fact and it has been demonstrated by Johnston and Negli. In a system which is already stressed by high temperature, the addition of an unbalanced stress serves to strain the organization of the molecules and to break up their internal structures—that is, to melt the rock. To accomplish this result the unbalanced stress must supply the energy for latent heat. Thus the action is limited to the available energy in the strain. It is also limited to the molecules involved. In case the strain occurs only on an individual shearing plane, the melted rock would constitute a very thin sheet; but if the strain extends to many closely spaced shearing planes, the thickness of the melted layer may be notable.

In the body of the earth unbalanced strain is due to shearing stresses which may originate in any one of several causes. A shearing stress may be set up by changes in speed of rotation of the earth, by cumulative tidal pull and compression, and, in case magma moves, by shifting of supporting pressures. Similar stresses may be produced by recrystallization with change of form, as in the metamorphism of deeply buried rocks. The potent molecular forces are brought into play by a rise in

[15] C. R. Van Hise: Metamorphism. U. S. Geol. Surv. Mon. No. John Johnston.

temperature, and if directed by unequal pressures may exert forces of exceedingly great intensity.

Of these several causes of possible melting strain we may rule out changes in the rate of rotation of the globe as being too slow and general for the geologic rhythm. The one which appears to be an ever-present force, and possibly adequate when cumulative, is tidal stress in the deep interior. Any movements of magma or effects of recrystallization follow on other disturbances and therefore can not be regarded as primary causes.

In considering melting as a change of condition which is possible in the interior of the earth, we are, of course, restricted to the solid envelope, since the inelastic core is regarded as probably already in the molten state. It is evident that the contact zone of the core and envelope would be a critical region. We proceed then to consider the conditions of pressure, temperature, and stress in that zone.

Autogenous Dikes

At the surface of the supposed molten core the pressure exerted by the weight of the surrounding shell is calculated to be 1,600,000 atmospheres, or something over 200,000,000 pounds per square inch (14,000,000 kilograms per square centimeter). The solid shell is compressed far beyond the degree which closes all interstitial spaces and at least may be supposed to reduce intermolecular distances. Mechanical development of an opening is inconceivable. If the globe were at rest, the confining pressure of the envelope would be resisted at all points equally by the hydrostatic resistance of the core. It would be impossible that any eruption of magma should take place against the overwhelming gravitative pressure.

The globe, however, is not and never has been at rest. It has always rotated. It has always been subject to tidal stresses of sun and moon. Heterogeneous masses, whether original or secondarily developed, have produced heterogeneous resistances in its body. Contacts of unlike masses, differing in elastic resilience and in strength, are surfaces where repeated strain will accumulate. Tangential, torsional, and diagonal strain are indicated by analysis of the forces. At this moment, however, we are less concerned with their orientation than with their dynamic affect in promoting fusion.

We may consider the conditions in an inner layer of the envelope, which we take to be a few kilometers thick, as being close to the melting point because it is in contact with or in immediate proximity to a molten mass of the same or nearly the same composition. Coincidence of a

change in composition with a change of state in passing from the core to the envelope would be possible, but the probabilities are against it. The position of the zone has been reached either by descent from a higher level in a cooling globe or by rise from a lower level in a globe that is heating up, and is determined by temperature conditions rather than by those of composition.

In this inner layer of the envelope the material is assumed to be a crystalline solid under conditions of temperature-stress which tend to melting. Considering tides as a cause of added mechanical stress, we may note: that they are greater in the body of the earth than at the surface; that they revolve round the earth every twenty-odd hours; that they produce shearing stresses in the earth across radii to which the moon's attraction is tangent, together with tension stresses between these radii and compression stresses outside of them. The high tide toward the moon is pulled up from both sides and a similar effect is produced opposite the moon. Thus, as the moon revolves around the earth, maxima of tension and compression alternate approximately every twelve hours.

In this movement there is a lag behind the position of the moon, and the amount of lag varies with the elastic properties of the material. In discussing this effect, Dr. F. R. Moulton pointed out the important fact that the lag of the tide behind the moon would not be the same in the inelastictic core and the elastic envelope. The two distortions would therefore not be in phase—that is, the high tide in one would not be over the high tide in the other. Quite the contrary might be the effect, according to the degree of inequality in the lags. The variability of lunar tides and their variable relations to solar tides result in great complexities of coincidences or differences. Here is a definite source of notable stress.

Assuming that, as seems inevitable, there are diverse masses in the inner layer of the envelope next to the core, there would be an irregularity in the rise of the tides against any more resistant surface—somewhat as the tide rises on a shore. But in the body of the earth we are dealing with continuous substance and the effect would be to strain the contact. Heat would be developed by the work done and would be very slowly dissipated in the hot rock. The strain would recur in twelve hours and would again develop heat. Sooner or later the small increments of temperature would accumulate to the degree at which melting of the strained layer of the envelope would ensue.

Considering the incessant repetition of these tidal effects, they suggest rather potent possibilities, but there are definite limitations to the action

of the stress. It can produce heat only so long as it works against a resistance, and the resistance ceases to be effective as soon as melting occurs. A very thin molten layer will act as a lubricant between rock masses and will facilitate displacement, with no more mechanical work than is involved in overcoming the friction. The friction, being converted into heat, tends to promote fluidity and thus to facilitate displacement. The ultimate effects of these reactions are involved in the conditions of growth of the shear; but we must first consider its orientation.

An oblique position is indicated by mechanical principles as the probable orientation of any such shear, since it should lie at an angle of approximately 45 degrees to the dominant pressure of gravity and the resultant horizontal compression of the spherical shell. Melting on a plane of shear thus directed obliquely outward would produce a dikelike body, equivalent in form to an intrusive, but originating *in situ* and distinguished from its walls only by a change of state. Such a body may be called an *autogenous dike.*

The manner of growth of an autogenous dike follows immediately from the conditions of its origin. The resistance on the initial surface having been reduced by melting, and displacement being thus facilitated, the tidal thrust would be transmitted as a shearing stress to the upper end of the autogenous dike, and the constant repetition would tend to promote the growth of the dike outward. The film of magma would transmit the hydrostatic pressures of greater depths to higher levels, where they would meet with less resisting pressure and would serve to promote the outward growth. The kneading action of alternate tension and compression would force gases upward through the film, and their solvent activity would be added to the conditions favoring the upward advance of the dike.

Considering the persistence of the mechanical and physico-chemical conditions which promote the growth of an autogenous dike, there might at first sight seem to be no reason why fissures of that type should not traverse the entire envelope on a diagonal curve, always approximately at 45 degrees to the radii which they successively traverse. The life of the lower edge of the dike as a fissure filled with magma is, however, limited by the conditions of pressure. As already noted, the law of hydrostatics requires that the pressure induced by the weight of the envelope resting on the core should be transmitted to the upper edge of the dike, where it meets with less resistance, and at some level would overcome that resistance to the extent of enlarging the fissure. The autogenous magma would then not suffice to fill the upper portion, and the defect would be

supplied from below, with the result that the fissure would be closed at the bottom. It would probably weld under the pressures and at the temperature there existing, but would remain as a scar and would be liable to reopen on repetition of the conditions.

The number of such initial autogenous dikes is a function of the accidents of constitution of the interior and is, of course, wholly speculative. They can not be too closely spaced, for any one would affect the rise of the tide in a segment lying to the west of it. Yet it is probable that we may assume a sufficient number of unlike masses in the inner spherical surface of the envelope to distribute autogenous dikes at various intervals around the sphere. Bearing in mind the object of our study, the origin of continents, we might consider whether the spacing of autogenous dikes had any relation to the arrangement of the continents. It is possible that such a relation exists, but it can not well be traced except in the oblique orientation of the northeast-southwest and northwest-southeast trending continental margins.

This last suggestion of a possible relation between very deep-seated causes and superficial effects depends on the fact that the tidal stresses pass from east to west around the earth, and if they produce any shear at all must cause that shear to develop along northeast-southwest or northwest-southeast lines. Inspection of any globe shows that this orientation is not uncommon and the explanation fits the facts. There are, however, many exceptions, especially those having rounded outlines like the Gulf of Mexico, and they also demand explanation unless we are content to attribute the major geographic features of the earth entirely to accident. Such a course rather offends one's intelligence.

Our speculations have now brought us to the point of recognizing the existence in the earth of molten films, autogenous dikes, which, though cut off at their roots, may continue to grow along the oblique paths determined by the dominant pressures, their growth being constantly stimulated by the repeated action of tidal stresses. Their persistence depends on relations of temperature, pressure, and constitution. The actual magma at any stage of their advance retains the heat of a lower level minus the loss which has been suffered by conduction into the cooler walls. This is an extremely slow process and it would probably require a long time for such a dike to congeal, even if it remained quiet. Furthermore, heat is being contributed by the work of friction as the walls strain past each other in repeated tidal impulses. At the upper end slight excesses of temperature and hydrostatic pressure combine with the repeated action of the tides to produce strain-melting and to cause the dike to grow. At its lower end it is likely to be closed in consequence of

the rise of magma into any expansion of its upper section. These conditions must ultimately lead to the advance of the autogenous dike from the deeper zones of the envelope to its outer portion. They thus constitute magma by which heat may be transferred from lenses of great depths to the outer shells of the earth. We shall see that this concept enters into the ideas by which we explain the development of larger bodies of magma in the asthenosphere, the sphere where fusion is facilitated.

Lest it may be thought that we attribute too great a potency to the action of mechanical strain in promoting melting, attention is called to the melting of drill cores at depths of only a few thousand feet. For instance, in a case which has been described by the Geophysical Laboratory of Washington,[16] melting resulted from the very slow turning of a 4-inch steel casing at a depth of 4,300 feet under a load of 20 tons. The rate of movement was 20 feet per minute, and the drill penetrated shale and sandstone to a depth of 3 feet. It then stuck because the core barrel was filled with molten slag. In producing this result the very low conductivity of the rock played an important part. A similar rôle is assigned it in connection with the phenomena of strain-melting which has been discussed. It is not the absolute but the cumulative significance of stress that we have to consider in connection with earth processes.[17]

We have discussed autogenous dikes as individual phenomena, but they would be so only in so far as their orientation was determined by accidents of heterogeneous structure in the envelope. The laws of shear require parallel series, and we may conceive at least two series of parallel strains that might produce autogenous dikes. They are indicated in plate 8 (frontispiece). Looking from the south at an equatorial section of the earth, a principal series appears as rising toward the west, while a minor series, crossing at right angles, rises toward the east. On the former series the shearing effect of the tidal stress as it moves from east to west is upward; on the second it is downward. The former would meet with less resistance than the latter and would therefore be better developed.

These relations suggest that the structure of the envelope is an ascending spiral one, rising toward the west, and oriented in azimuth from northeast to southwest and from northwest to southeast. Special condi-

[16] N. L. Bowen and M. Aurousseau: The melting of sedimentary rocks in drill-holes. Bull. Geol. Soc. Am., vol. 34, 1925, pp. 431-448.

[17] John Johnston and L. H. Adams: On the effect of high pressure on the physical and chemical behavior of solids. Amer. Jour. of Science, fourth series, vol. xxxv, 1913, pp. 205-253.

tions might give the second series, rising toward the east, local importance. The usual concept of a globe split by dikes that rise radially appears to be inconsistent with mechanical principles under terrestrial conditions.

Three Shells of the Envelope

According to the concepts we have thus far discussed, two major regions divide the interior of the earth between them: the hot, highly viscous, inelastic core and the relatively cool but heated elastic crystalline envelope, which is normally solid, but from time to time, at one place or another, is shot through and through with autogenous dikes temporarily melted *in situ*.

The elastic envelope is roughly 3,200 kilometers (2,000 miles) thick. We may now divide it somewhat arbitrarily into three shells: the innermost, which is the strong envelope we have been discussing; a middle shell; and the outer crust, or skin. The thicknesses assigned to these shells are, respectively, 1,900 kilometers (1,200 miles), 1,300 kilometers (770 miles), and 50 kilometers (30 miles). In stating these round figures exact equivalents are avoided, because the thicknesses themselves are quite indefinite. They represent shells which are determined by probable differences of temperature, pressure, and structure, as well as by variations of composition and facility of melting or movement. They are, therefore, without definite spherical limits, they grade into each other vertically, and the passage from one to another will lie at different depths under different geographic positions. The extent of their vertical ranges is quite indeterminate, but fancy is set a certain limit by the nearly unifom attraction of gravity over the earth's surface and by the sameness with which earthquake vibrations speed through distinct sectors of the envelope. The figures given above serve as well as any others to indicate the respective shells.

It is desirable to characterize the three shells according to the specific conditions by which they are distinguished, theoretically. These conditions are primarily temperature, pressure and the state of matter (solid and elastic or molten and viscous), imposed by the control of pressure over temperature or of temperature over pressure.

The Stereosphere

A new term is here introduced to designate the innermost shell surrounding the core and extending out from it some 1200 miles. We will call it the *stereosphere*, or strong sphere. Seismology shows that it

is solid and highly elastic, but also that the speed of earthquake waves falls off inward.

In regard to the changes in velocity of waves, Macelwane [18] says:

"From the depth of about 60 kilometers down to 1,200 the velocity of earthquake waves increases rapidly with depth. . . . The rate of increase of velocity is almost a linear function of the depth within this range. . . . From 1,200 to about 1,700 the increase is more gradual."

The velocity continues to increase, but still gradually, down to 3,450 kilometers, below which it falls off to where the waves enter the core.

The velocities reflect the effect of a contest between the elasticity and density of the medium. They increase with the former's increment and decrease as the latter gains.

Both density and elasticity should increase with pressure inward, but there is some condition that reduces the influence of elasticity and causes the velocity of waves to fall off. The full effect of that cause is observed in the core, which is inelastic presumably because of very high temperature. Similarly the relative degrees of elasticity in the stereosphere may be attributed logically to temperature conditions. The stereosphere is everywhere normally below the melting temperature for the actual pressure, but the amount by which its condition falls below the melting point increases from within outward. Its inner position, next the superheated core, is relatively near melting; its outer layers are relatively far below the melting point.

The Asthenosphere

Having discussed the stereosphere, our attention is now directed to the next one. It is distinguished by relatively effective temperature, as contrasted with pressure, according to Chamberlin,[19] who wrote:

"If the earth grew up by slow accessions of planetesimal matter, and if its interior heat is chiefly due to compression by its own gravity, the internal temperature would be originally distributed according to the degree of compression, and this would depend on the intensity of the internal pressure. . . . Our not improbable assumptions regarding the thermometric conductivity, the flow of heat from the deep interior to the middle zone, would be greater than the loss of this zone to the superficial zone. This middle zone should in this view experience a rising temperature."

The not improbable assumptions of the preceding postulates relate to the supposition that thermal conductivity stands in some relation to

[18] J. B. Macelwane, S. J. The Interior of the Earth. Bull. Seism. Soc. Am., Vol. 14, 1924.

[19] T. C. Chamberlin and R. D. Salisbury: Geology, 2d ed., vol. I, p. 269, hyp. 7; and also Thermal distribution under the accretion hypothesis, 1909, pp. 564-565.

compression. We have already discussed the conditions of conductivity and reached the conclusion that they must result in gradients that would vary materially along different radii. At the same depth some parts of the earth would be hotter, some cooler. Lateral flow of heat is, of course, a necessary consequence, and its relative importance would depend upon local conditions. In considering general temperatures we refer to the studies of Lunn,[20] made under the direction of Chamberlin, on the mean heat gradient of the earth; the bottom of the zone of rising temperature lies about 800 miles below the surface. This we accept. Barrell[21] developed Chamberlin's idea and named the shell of relatively high temperature the *asthenosphere,* or sphere of weakness. The implication is that the relations of temperature and pressure are so nicely balanced in the asthenosphere that a slight increase in temperature or decrease in confining pressure may cause local melting and consequently a loss of strength in a particular region. The Chamberlin-Lunn estimate of the probable depth of the inner surface of the asthenosphere (800 miles) may be checked by seismology.

Macelwane, whose estimates of the thicknesses of elastic shells of the earth we have already quoted, describes the shells from the point of view of the seismologist as follows:

"We find ourselves living on a planet with a surface layer of rock, in places at least, 60 kilometers deep, lying on a mantle of much more elastic material, probably rock, about 1,100 kilometers thick."

This takes us to the bottom of the asthenosphere, as determined by Chamberlin's estimates.

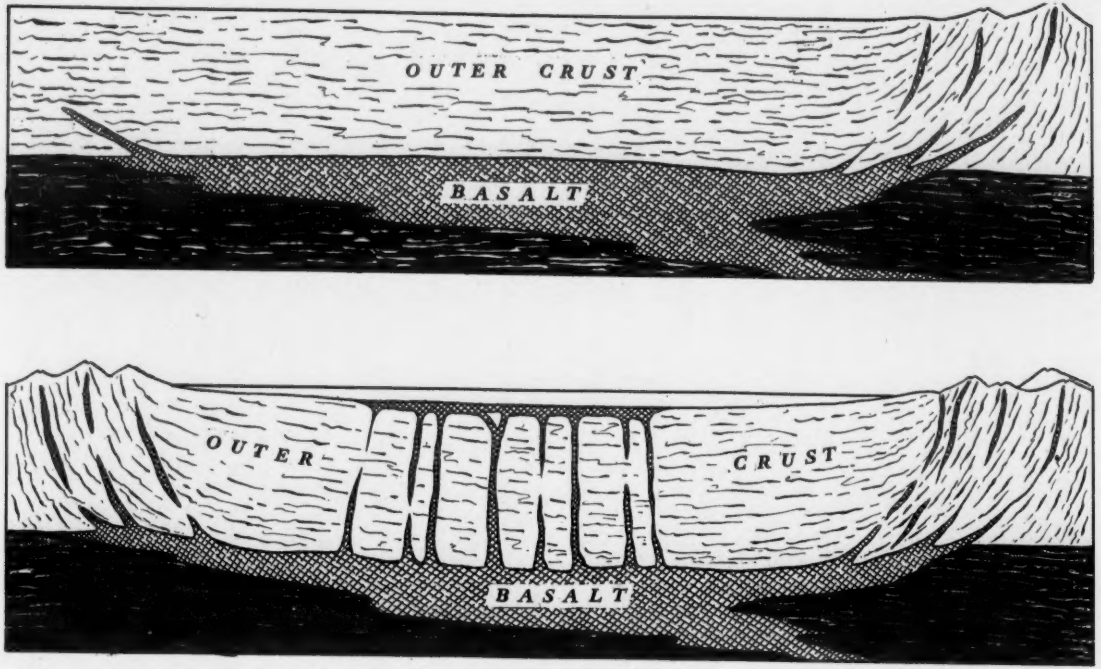
It must be obvious that we are here speaking of the asthenosphere as solid and highly elastic. It is important to emphasize the fact that that is its condition, as we understand it. The term sphere of weakness is strictly relative and applies to the general approach of the material to the temperature at which it will melt; but no such concept as that of a molten shell is entertained, though the temporary melting of relatively small portions is regarded as a recurrent condition, which is demonstrated by the occasional rise of the granitic and basaltic magmas that have solidified in the outer skin and constitute its mass.

The outer Crust, or Skin

The existence of the outer skin as an external layer distinct from, though grading into, the asthenosphere is indicated by experimental

[20] A. C. Lunn: Op. cit.

[21] Joseph Barrell: The strength of the earth's crust, the asthenosphere. Journ. of Geol., vol. xxii, 1914, pp. 680-683.



OUTER CRUST OR SKIN

and seismological data. On grounds of inference backed by experiments, it may be described as the *zone of fracture*, including granulation and microscopic fracture of the hardest rocks. First defined by Van Hise in his studies of the Precambrian, it is now known to extend to much greater depths than he thought probable. Its bottom surface, at which it passes into the asthenosphere, is determined by the fact that even submicroscopic pores are closed by the superincumbent pressure. Adams' [22] experiments show that this condition must be reached at a depth in the neighborhood of 30 or possibly 35 miles (48 to 56 kilometers). Above that minute pores are possible and fractures of larger dimensions become common as we approach the outer surface. Thus, the zone of fracture is the zone in which discontinuity of rock substance affects all physical and mechanical reaction. On the other hand, below the zone of fracture, in what Van Hise called the *zone of flow*, absolute continuity of substance is imposed by the states of pressure and temperature. This is the condition in the upper part of the asthenosphere and throughout the rest of the globe.

The seismologist recognizes the position of the bottom of the zone of fracture as that of a surface from which earthquake waves are reflected. It is known as the "surface of discontinuity." In Europe [23] its depth has been determined to be 57 and in California [24] about 50 kilometers.

These depths agree closely with the experimental results of Adams and strongly suggest that the sharp change in elastic properties is due to the passage from the zone of fracture to the zone of flow, as defined above.

While qualitatively sound, the preceding conclusion is quantitatively inadequate. It is in the same class with the assumption formerly made, that the high density of the interior of the earth could be accounted for by compression. The experimental work of F. D. Adams [25] and L. H. Adams [26] has demonstrated that mechanical compression is not adequate to produce the required density. Greater molecular density—that is, different mineral composition—is required. The very material

[22] F. D. Adams: An experimental contribution to the question of the depth of the zone of flow in the earth's crust. Journ. of Geol., vol. xx, 1912, pp. 97-118.

[23] S. Mohorovicic: Das Erdinerre. Zeitschrift fur angewandte Geophysik, I, 1925, Heft 11 and 12.

[24] Perry Byerly: The depth of the surface layer in California. Bull. Seis. Soc. Amer., vol. 16, 1926, pp. 1-9.

[25] F. D. Adams and E. G. Coker: An investigation into the elastic constants of rocks, more especially with reference to cubic compressibility. Carnegie Institution, Publication No. 46, 1906.

[26] L. H. Adams and E. D. Williamson: The compressibility of minerals and rocks at high pressures. Jour. Franklin Inst., vol. 195, 1923, pp. 474-529.

increase in the velocity of earthquake waves at the "surface of discontinuity" is too great to be wholly due to mechanical compression. It indicates a change in mineral character. The observed velocities in the deeper layer beneath the skin correspond most nearly with those calculated from the compressibility and density of a rock which is more basic than gabbro and approaches dunite in composition.[27] Hence it is more than probable that the granitic rocks which make up a continent rest on denser, more basic rock, related to dunite. The mechanical and molecular conditions combine to give the elasticity which speeds up the earthquake waves.

Although called the zone of fracture, the outer skin is exceedingly tough. On the basis of Adams' experiments, Willis [28] has shown that at a depth of four miles (6 kilometers) below the surface of the earth it is five times as strong as it need be to carry the load that rests on it. Its strength increases with the growth of pressure due to load as depth increases, but not so fast. Hence the load overtakes the strength at 30 to 35 miles below the surface, and load and strength are there equal. This is the condition under which all mechanical pores must close. As we have already seen, it characterizes the level at which the zone of fracture passes into the zone of flow. We may not, however, consider such rock as weak with reference to unbalanced stresses, although overloaded by confining pressure. It would require an unbalanced pressure in excess of 200,000 pounds per square inch (14,000 kilograms per square centimeter) to cause shearing.

The bottom of the zone of fracture, corresponding with the inner surface of the outer crust, or skin, is an important level in connection with this study, because it appears to represent the upper limit of that condition of local melting which is characteristic of the asthenosphere. We do not intend by this to exclude the possibility of melting at higher levels through any cause whatever, but to emphasize the characteristic of the asthenosphere.

We attribute the establishment of a distinction between the asthenosphere and the outer crust to the more gradual escape of heat through the relatively porous rock of the latter. Below, in the asthenosphere, all interstitial pores are absolutely closed. The transmission of vibrations from one molecule to another should be prompt and effective.

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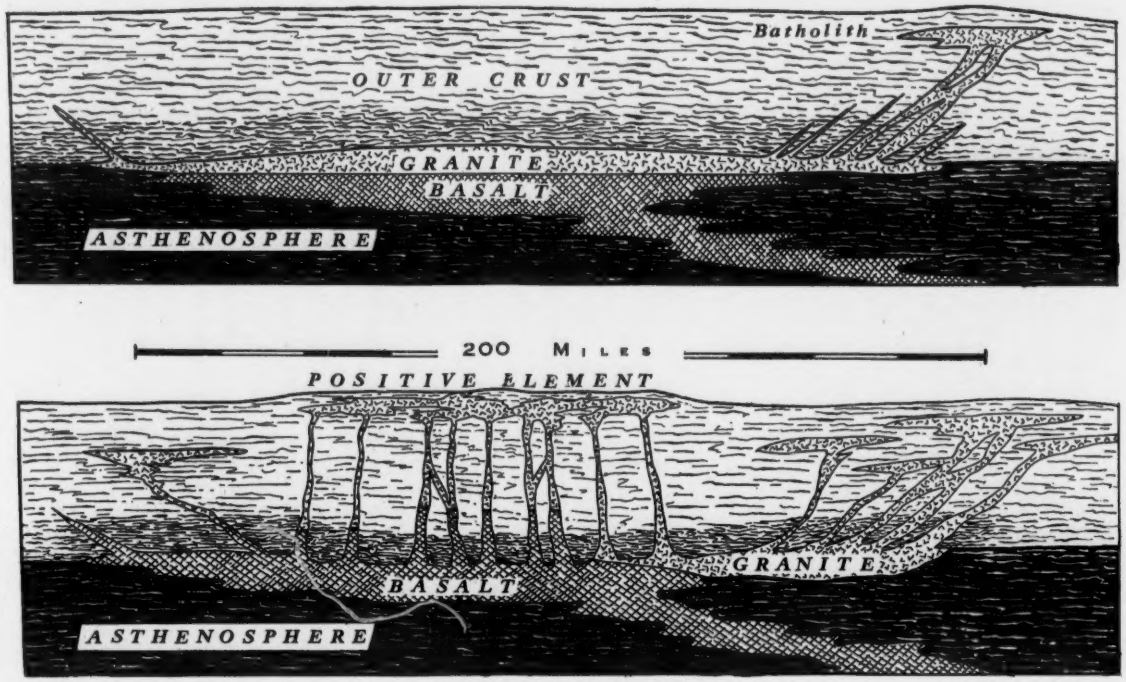
[27] L. H. Adams and R. E. Gibson: The compressibilities of dunite and of basaltic glass and their bearing on the composition of the earth. Proceedings of the National Academy of Sciences, vol. 12, 1926, pp. 275-283.

[28] Bailey Willis: Discoidal structure of the lithosphere. Bull. Geol. Soc. Am., vol. 31, 1920, pp. 252-256 and plate 8.

CONTINENTAL ASTHENOLITH



CONTINENTAL ASTHENOLITH

Above, in the zone of fracture, minute pores or major spaces are assumed to exist as a consequence of any competent deforming strain or as a result of metamorphism. The loosened molecular structure or microscopic sponge would not transmit heat vibrations as effectively as would the densely compacted rock of the asthenosphere. If this conclusion be sound, the outer skin would constitute a layer beneath which heat would commonly accumulate. Its under surface would therefore cover a zone peculiarly well conditioned to be the habitat of local melting. This does not, however, exclude the occurrence of similar conditions and effects at greater depths in the asthenosphere and even in the stereosphere where heterogeneous masses are in contact.

ASTHENOLITHS

Melting is the characteristic reaction of the asthenosphere, in consequence of the concentration of heat energy chiefly through slowing up of conduction from within outward. If we conceive the zone, which is over 700 miles (1,100 kilometers) thick, to be uniform in constitution, the distribution of temperature would be correspondingly regular; or, if we think of the shell as heterogeneous and more or less irregularly stratified, the heat would vary accordingly. The latter condition is indicated by all the available evidence and may be accepted as the basis for further analysis.

We postulate, then, an asthenosphere of igneous rock that has had a long history of repeated local melting and solidification and has become rudely stratified in sheets and parallel intrusions. The conduction of heat outward through the layers will vary in rate and local increments of heat will result under any relatively non-conducting sheet. When the increment beneath any sheet becomes sufficient, melting will result and a lenticular molten mass will be formed. Such a body of magma I propose to call an *asthenolith*.

An asthenolith may be defined as a body of magma formed in consequence of a rise of temperature in the asthenosphere because of concentration of heat energy. Such concentration may result from an autogenous dike, either by conduction or directly from the magma; or conducted heat may accumulate under a relatively non-conducting layer.

The conditions for the formation of an asthenolith may obviously occur at any depth, but they may be most effective and widespread just under the outer skin, where the most pronounced check to conductivity is supposed to occur.

It will be well to consider the manner of growth of an asthenolith. By postulate it is a body of magma produced in the asthenosphere in

consequence of a temporary and local rise of temperature. The terms local and temporary are to be taken in a geologic sense, in relation to the dimensions of the globe and the duration of geologic ages. The original source of the heat is assumed to lie in the work done in the interior of the earth. It is thought to fluctuate in amount, in the very nature of the processes of growth and stress, and consequently to produce more or less heat energy from epoch to epoch. The outflow of heat is also irregular, because the conditions of conduction, absorption as latent heat, transfer in molten masses, release during solidification, etcetera, many times repeated, must result in irregularities.

The conditions that cause the delivery of heat to the asthenosphere to be irregular will affect its passage through that zone and will be accentuated there; hence, the growth of an asthenolith will have its beginning, development, and final stages.

Passing over the initial episodes, which involve the beginning of the melting of the rock *in situ,* we may consider the asthenolith during its period of growth. After melting has begun and so long as it is in progress, the temperature of the magma must remain practically constant, since the slow increment of heat will be absorbed in the additions to the solution. To a certain extent, this uniformity of temperature will be modified in a large mass by the evolution of gases and their rise through it. In general the conditions may be regarded as favorable to differential solution and gravitative segregation.

The deepening of the asthenolith will be impeded by pressure. There will be a tendency to eat into the cover, where the active gases rise, but the conditions of advance will be limited by the relatively low temperature a short distance beyond the magma. More favorable environment for growth will be found around the upper margin, at the edges, where the solution can penetrate into rock at similar temperature and also be aided by the gases.

If this analysis be correct, the magmatic body of the asthenolith will spread laterally and gain in diameter while remaining relatively thin in vertical dimension. It will thus tend to exaggerate the initial disproportion of these dimensions, which may be anticipated. Its vertical section will be that of a lense and its horizontal plan will be round, oval, or branching into oval forms.

The growth of an asthenolith may be limited by a change in the heat supply, already assumed to be irregular; or the lense of magma may reach such a diameter that the cover can not support the strains imposed on it and will rupture. The growth of stresses, the development of strains, and the conditions of rupture require careful consideration.

During the growth of an asthenolith, before any rupture occurs, the blister of magma is sealed in by the solid, crystalline rock that surrounds and covers it. The weight of the cover rests on it as it did on the solid which has melted. The cover is not immersed in the magma, and there is consequently no effect of buoyancy. At a depth of 30 miles below the surface of the earth—that is, under the skin—the gravitative pressure is about 200,000 pounds to the square inch (14,000 kilograms per square centimeter), and it increases proportionately with depth.

In the usual condition of the earth's crust there is stability, because the weight is supported by the resistance of the foundations to further compression and because all lateral stresses are balanced. If the material in the zone of flow were a perfect fluid, the excessive load would cause a lateral pressure equal to the load. We would then have hydrostatic pressures in all directions. But this condition does not exist, because we are dealing with an elastic solid. Any small part that we may conceive to be represented by a cubical element of that solid opposes elastic resistance to deformation, or, if the elastic limit be surpassed, opposes its strength to shearing. Thus the condition of stability is that the resistance of the solid plus the horizontal pressure equals the load.

When heating disturbs the normal state of balance by weakening the shearing strength of the rock, the horizontal pressure increases proportionately and throughout the area thus affected. We are thinking of the cover of a growing asthenolith. Supposing the weakening to begin near the center and to spread with the expansion of the blister, there must be set up in the cover a horizontal pressure greater than that which exists around the margin at the same level, due simply to the weakening effect of heat. The appropriate expansion due to rise of temperature would work with this, but their sum would remain less than the vertical stress due to load so long as the rock was solid. A greater stress, however, can be produced by the molecular force of recrystallization.

The last statement depends on the development of schistosity. It appears inevitable that the rocks of the cover should adjust themselves to the change of stress environment. We may assume that they were in part schistose, in part holocrystalline, resembling an Archean complex. The orientation of schistosity in the schists will have been inherited from some previous arrangement of stresses. In so far as it agrees with the actual arrangement it will persist, but in so far as it differs it must readjust itself. The holocrystalline rocks must become

schistose. The appropriate orientation is horizontal. The molecular forces, stimulated by heat, will be directed horizontally against the inert masses around the margins of the asthenolith. We shall recur to this important effect in discussing the eruptivity of an asthenolith.

Lest the discussion of asthenoliths should convey the impression that no other type of igneous body might form in the asthenosphere, it is desirable to recall the genetic conditions of autogenous dikes. They are attributed to strain in a heated but solid mass. Strain, if caused by variation of the rate of rotation or by tidal stresses, is much greater in the interior than in the outer shells of the globe; but the absolute stress is less significant in connection with possible melting than the relation between stress, temperature, confining pressure, and the approach of the rock to that critical point where it is about to melt. The restraining effect of pressure is relatively low in the asthenosphere; the temperature is high. It follows that even moderate stresses may be able to establish strains that will promote melting. We must therefore recognize that autogenous dikes may develop in the asthenosphere, and that they may extend outward to and into the outer skin itself. The structure of the asthenosphere thus appears as a complex of lenticular sheets and dikes.

Differentiation in the Asthenosphere

The essence of our thesis is that the continents consist of granitic rocks which have been separated by processes of differentiation from the more basic types that form the greater mass of the globe. We must therefore consider the conditions affecting these processes. It will be necessary to take account of the material contributed to the asthenosphere and the differentiation that may take place in the asthenoliths.

According to the concepts already set forth, the asthenosphere has been fed by autogenous dikes rising from the deeper envelope. They are supposed to have melted *in situ* and consequently to have represented originally the wall rock; but in working their way out, with repeated episodes of solidification and solution, they are thought to have acquired a modified composition which should represent the more or less acid, more or less basic, average of the segments of the earth they traversed. Considerable weight is given to this divergence of average products. It is believed to have had its origin in the cyclonic clouds of the original planetary bolt, to have been intensified by the concentration of silica by weathering during the stage of planetesimal infall and to have been a prime factor in determining the ultimate plan of the continents.

On arriving at and penetrating the asthenosphere, a dike would carry at its upper edge the products of assimilation and differentiation developed during its long, oblique ascent through the 1,200-mile envelope, in course of which it had crossed innumerable other dikes and traversed heterogeneous substances gathered by the growing earth during the infall of the planetesimals. Originally slight differences would thus be notably increased in the asthenosphere.

Differentiation would continue there under the influence of high temperature and with an indefinite time allowance. We may not forget that an asthenolith possesses the fourth dimension—time—as well as length, breadth, and thickness. Its life comprises a prolonged stage of gradual heating up above the normal temperature for its depth in the asthenosphere. Then follows the gradual process of melting, during which the contribution of energy from within the earth is transformed into latent heat and the temperature can not rise, except through the convection of heat with rising gases. The upper portion would thus tend to become hotter. Local differences of heat supply, side by side, along dikes or through unlike bodies of larger size, and rhythmic waves of heat may reasonably be postulated. The general progress of melting will proceed unevenly, with incidents of partial recrystallization and remelting. During each state the molecular forces will tend to strike the most stable balance consistent with their environment. The soluble and insoluble, the light and the heavy, the acid and the basic, will tend to separate in the magma and to assemble in distinct bodies or layers within the limits set by the viscosity of the mass.

We here depend upon the present state of knowledge regarding the behavior of minerals under high pressures and at high temperatures; but there can be no doubt that the processes of differentiation demonstrated by the experimental work of Vogt, Bowen, and other petrologists must come into play and would have space and time to accomplish large results through successive reactions.[29]

According to our assumptions, the magma which constitutes an asthenolith or which develops in connection with it ultimately escapes by eruption through the outer skin of the earth. The fraction escaping during any one episode is usually but a small part, as is indicated by

[29] J. H. L. Vogt: Silicatschmelzlosungen. The physical chemistry of the crystallization and magmatic differentiation of igneous rocks. Jour. of Geol., vol. xxx, 1922, pp. 659-672.
N. L. Bowen: The later stages of the evolution of igneous rocks. Jour. of Geol., Supplement to vol. xxiii, 1915.
Ibid: The problem of anorthosites. Jour. of Geol., vol. xxv, 1917.
Ibid: The evolution of igneous rocks. Princeton Univ. Press, 1928.

the succession of diverse types of intrusives observed at the surface, and the long-continued process of eruption may be regarded as a normal feature of the life of an asthenolith. A little consideration of the relatively sudden variations of temperature and pressure incidental to eruption and unloading will suffice to indicate that vigorous reactions must ensue in the remaining magma. The experiments made nearly fifty years ago by Hannay, on the absorption of gases in solids and their release on reduction of pressure, are still instructive.[30]

Eruptivity of an Asthenolith

While the life of an asthenolith must be estimated as long, even in geologic terms, it can not be without limit. We conceive the molten lense beneath the outer layers of the earth at depths of 30 miles or more to be a source of eruptive activity, and its life would continue as long as it continued active. It is probable that there are active asthenoliths today beneath the Caribbean, Atacama, Tonga, and Mediterranean deeps. At least it is logical so to regard those basins whose rims are the scene of voluminous volcanic activity. But there have been other asthenoliths, such as those of the Precambrian, which constitute the nuclei of the continents as we interpret them. They have long been dead. Thus we are brought to consider the conditions that affect the eruptivity of an asthenolith and set a limit to its activity.

The cover of an asthenolith is at least 30 miles (48 kilometers) thick and may be several hundred. It is strongest, densest, in its lower part, a short distance above the molten mass, within reach of the high temperature and where pressure is greater than it is nearer the surface. These conditions oppose the maximum resistance to penetration by an intrusive tongue which might otherwise be thrust out by the magma.

There is little reason to assume uparching of the cover during the long period of gestation. The volume of magma is augmented only by rise of temperature and change of state, not by voluminous influx, according to the genetic postulates; consequently the cover would not be in tensile stress because of intrusion beneath it.

The vertical forces opposed to one another at the contact of the magma and the cover are the weight of the cover and the hydrostatic resistance of the magma under its pressure. They are equal and directly opposed at any point. They offer no condition of unbalanced stress which might cause rupture. They do, however, constitute a kind of vise which exerts a vertical compression, especially upon the lower

[30] J. B. Hannay: On the absorption of gases by solids. Phil. Proc., vol. xxxii, 1881, pp. 407-408.

layers of the cover. If the latter undergo metamorphic change, the schistosity must be oriented accordingly, in a horizontal attitude, as we have already observed.

All the conditions discussed work for stability of the cover of an asthenolith and are therefore in accord with the very significant evidences of stability that we observe in the geologic record. Instability is the exceptional, the revolutionary, condition of the surface of the globe.

Nevertheless, eruptions from asthenoliths or similar bodies do occur and are accompanied by revolutionary changes of surface features. They occur at the close of a long period of preparation, when an asthenolith has reached its limit of growth. The dynamics of the system become unstable when the diameter becomes too great.

The thick cover does not float in the magma in a position of buoyancy. It bears on the liquid with its weight of 200,000 pounds per square inch (14,000 kilograms per square centimeter) or more, seeking a position of buoyancy. There are, however, no openings in the zone of flow, and there is no opportunity for intrusion into the cover, so long as the balance is undisturbed. The balanced condition of stresses becomes more and more uncertain as the diameter of the asthenolith grows. The tidal pull produces an alternation from compression to tension every six hours. The wave that follows it in the magma induces strain in the cover and is itself accompanied by gas emissions. The accumulated strain must impinge against the margin, against the adjacent solid segment, and will there exert an effect that increases as the diameter increases. The horizontal thrust due to weight and metamorphism will set up shearing stresses, which may produce autogenous dikes or mechanical shearing. Marginal rupture will result in marginal eruption. The lateral outflow of magma will be followed by subsidence of the crust with development of tension in the under side of the cover at some distance back from the margin, and dikes will then intrude along the more direct paths thus opened upward.

We may regard this process as characteristic of the development of basins. Over the major part of the earth's surface the magmas erupted are basic. It is their habit in melting to pass from the solid to a relatively very mobile state within a short range of temperature. They are therefore capable of flowing long distances in the asthenolith, and if they reach the surface they spread out in thin but extensive sheets. These appear to be the features of the flat ocean floors, which are thought to be made up of the outflows from many asthenoliths.

Over the remaining one-fourth of the earth's surface the eruptions are typically granitic. The habit of the siliceous, feldspathic rock is to soften gradually through a wide range of several hundred degrees of temperature. It passes from a pasty to a fluid state only at a higher temperature than that which melts the more basic minerals, unless charged with gases, and if charged with gases the magma is relatively light. It will therefore float high. We have already assigned reasons for the assembling of acid constituents in certain parts of the body of the globe and their concentration in the asthenosphere. During the process of differentiation in the asthenolith they will tend to rise to the highest levels under the cover. The gaseous content will act as a powerful solvent and will penetrate outward on relatively slight opportunity. These conditions suggest the eruption of granitic magma from the uparched central section of an unbroken asthenolith or from the raised margin of one which has broken and sunk in.

We specifically emphasize the distinction between basic and acid eruptions, but the intermediate facies of igneous rocks will also be erupted. They may result from imperfect differentiation of an originally intermediate magma, or from remelting and assimilation, followed by cooling, under conditions unfavorable to differentiation, or from the action of controlling conditions that are yet to be discovered by physical and chemical research, of which there is urgent need. Whatever their mode of formation may be, it follows from petrographic studies that the intermediate facies constitute large masses in the visible continental areas, where there is a tendency to the more siliceous types, and it seems probable that the suboceanic rocks vary from moderately basic to ultra basic varieties. Evidence of the latter differences is suggested by the fact that the basins vary in depth. If that condition is a result of differences of density in a shell that tends toward isostatic equilibrium, then we must infer variety in the constitution of the rocks. The oceanic floors can not be all uniform basalt.

With these concepts of the conditions governing the growth and eruptive activity of asthenoliths in mind, we may now turn to inquire how the inferential effects on the surface fit the features we know, especially in relation to the arrangement of continental masses, their development, and their structure.

Arrangement of Continents

First of all, we are at liberty to assume, if we choose, that the actual distribution of continents on the globe is purely fortuitous; that it is

a fact which is the accidental outcome of an infinite number of complex reactions, too complex to permit of rational analysis. The philosophic mind of Chamberlin was not satisfied with that acknowledgment of intellectual impotence, and he has furnished an explanation which is a consistent part of the complete theory of the origin and growth of the earth, evolved by him in a long process of trial and modification of cosmogonic theories.[31]

It has long been recognized by geographers that the surface features of the earth are arranged in two hemispheres that differ in the proportions of water and land areas. They are known accordingly as the "Water Hemisphere" and the "Land Hemisphere." The continents are grouped in the latter around the North Pole. Chamberlin shows that the difference in density between the two sides of the globe, which this uneven distribution of land and water indicates, is inherited from the difference in density of the two ends of the bolt that was shot from the sun to form the planet. It is postulated by the planetesimal hypothesis that the bolt originated deep in the sun; it therefore represented a section of the sun and must have been composed of heavier substances at its rear end, in contrast to the lighter material of its outer end. The vestiges of this original condition appear to survive in the distinctive features of the Land and Water hemispheres.

The logic of this reasoning is sound and it explains the otherwise remarkable fact that the Pacific basin occupies nearly one-half of the earth's surface, while the continents are grouped on the other. These concepts agreed to, the question then presents itself: To what degree is the original structure of the bolt represented in the actual structure of the globe and in its surface features? The complexity of the structures and processes affords room for diversity of opinions.

Chamberlin reasons that the grouping of the continents has been influenced by atmospheric circulation, which from an early stage of growth of the earth onward effected a sifting of the lighter from the heavier planetesimals as they passed through the air and were wafted here and there in its ascending, descending currents. To appreciate fully the idea, the reader should refer to Chamberlin's own discussion.[32] The subhypothesis that is thus presented appears to me dynamically incomplete, in that it neglects the eruptive agencies of the earth, which are the sequel of those eruptive activities of the sun that have been so

[31] T. C. Chamberlin: The two solar families, 1928, pp. 178-187.

[32] T. C. Chamberlin: Origin of the earth. Chapter viii, The juvenile shaping of the earth, 1916, pp. 159-225. See, also, by the same author, The growth of the earth (in press).

happily recognized by Chamberlin as effective during the birth of the planet.

The problem of continental grouping within the Land Hemisphere thus invites me to take a path which here diverges from that followed by Chamberlin. Going back to the bolt from the sun, we may recognize that it was a cyclonic spiral, a funnel of rolling clouds of planetesimal substance, in which molecular organization was in progress and silicates of different kinds were formed. No better picture of its organization can be offered than that given by Chamberlin in "The Two Solar Families." He compares it to a cumulus cloud in which the rolling assemblage of droplets in a measure retain their independence while sweeping along in the revolving currents. This independence would be continued in the swarm of planetesimals, as they were drawn into their orbits about the sun, and would be perpetuated in the heterogeneity of the earth, at least to the degree that the infalls from any one portion of the swarm would be heavier or lighter than from another.

It is not to be assumed that the actual arrangement of the continents corresponds directly with that primordial organization. The eruptive processes within the earth have certainly intervened, and to them the major rôle of segregation is assignable. The method has already been suggested and is connected with the formation of autogenous dikes and asthenoliths.

The formation of dikes is attributed to unbalanced stresses and high temperature, and the former are believed to have been caused by variations in the rate of rotation and by cumulative tidal stresses. It has been shown that shearing planes, on which the autogenous dikes are supposed to be oriented, must occupy inclined rather than radial attitudes and consequently would not be oriented on radii of the spheroid. Any eruptive matter ascending along the dikes would therefore travel laterally as well as vertically. The dikes are supposed to have developed on at least two systems of shearing planes, and it would be conceivable that the intersections of the two might lie in a limited sector in such wise that the ascent of the material would on the whole be in a vertical sense. But the pull of the tides, which is thought to have been a controlling stress, is always from east to west, and it must have sufficed to determine a tendency toward an inclined path of ascent, with a predominant movement in that direction.

There is reason to think that assimilation would be favored during the development and ascent of the dikes, and that any system of them would therefore gather its constituents along its path. On ap-

proaching the surface it would represent the constitution of that segment which it had traversed, more basic beneath the Water Hemisphere, more acid beneath the Land Hemisphere, but in either one or the other subject to variations according to the inherited heterogeneity of the planetesimal infalls. On penetrating the asthenosphere the dikes would coalesce and form more or less basic magmas, presumably rarely distinctively acid.

Considering the important rôle thus assigned to the dikes in bringing to the asthenosphere magmatic products of somewhat diverse composition, it is appropriate to check the inference against the actual plan of the continental forms. We have noted that the rotational stresses, to which the development of the dikes is chiefly attributed, should result in shearing planes oriented from northwest to southeast and from northeast to southwest. This orientation might be expected to be reflected in the arrangement of unlike magmas in the asthenosphere, and to be carried on into the forms of the continents. It has often been noted that the continents point south, and that the diagonal trends cited above are characteristic of notable sections of their margins. The Tetrahedral theory of the earth, Chamberlin's fundamental segmentation, and other hypotheses have emphasized this major structure. It is here regarded as the expression of the arrangement of the deep-seated autogenous dikes, governed by rotational stresses.

Lest we be tempted to lay too much stress on this trend of outlines toward the southwest or southeast, we should remember that it is a secondary factor, subordinate to the division into the Land and Water hemispheres and modified in turn by the forms of masses developed in the asthenosphere. We may now turn to the latter.

Magmatic bodies in the asthenosphere are thought to assume three principal forms: (1) Intrusive or autogenous dikes developed by mechanical intrusion, or by strain-melting, or by a combination of the two; (2) stocks, where intersecting dikes concentrate the conditions of excessive temperature or strain around a central zone or chimney; (3) discoidal asthenoliths, formed by melting under a relatively nonconducting layer, either within the asthenosphere or immediately under the outer skin, in consequence of rising temperature and of the accentuation of other conditions favoring solution of the magmatic constituents.

Of the visible features of the earth's structure only minor ones may be assigned to the linear forms of dikes or the localized bodies of stocks. While apparently recognizable and significant, they can not be credited with an influence on the general plan.

It is otherwise with the asthenoliths. They are of great lateral extent and may reasonably be looked for in the arrangement of the protuberances and depressions of the surface. Seen in plan as in a map, an asthenolith should present a rounded margin, since its lateral growth is attributed to the solvent action of gases at high temperature in the magma. Complete circles or ovals would presumably rarely develop, the conditions being impulsive and irregular and the disks tending to interfere or coalesce with one another; but distinct outlines, so far as they may be traced, would be expected to be curved.

The rounded depressions which are the component parts of oceanic basins suggest an intimate relation between the superficial features and underlying asthenoliths, so far as form is significant. Arcuate island chains, mountain arcs, and the oval forms of the positive continental elements invite further comparison and investigation; but before we turn to the analysis of the visible forms and their connection with the asthenosphere, it is desirable to consider the formation of the outermost shell, of which they are the constituent elements.

Formation of the outer Shell

Let it be understood that the outer shell, or crust, or skin, to which these paragraphs refer is that layer on which we live and which is limited below by the "surface of discontinuity," at a depth of approximately 30 miles (48 kilometers) or more. Its bottom is the top of the asthenosphere and is presumably quite irregular.

The concept of the crust is very old and has assumed many forms, to suit different hypothetical processes of earth genesis. The idea of a crust formed by the cooling of a molten globe is the familiar one and is one that is supported by the fact that the skin of the earth consists of igneous rocks. There is no question but that the rocks of the outer shell have without exception all been melted at one time or another, as assuredly as have the rocks of the interior, and the simplest assumption is that the entire globe, or, at any rate, the whole of an outer envelope, has been simultaneously molten. But that is not the only possible, nor necessarily the most probable, assumption.

In order to get a different view point, let us consistently follow the reasoning of the planetesimal hypothesis, which we have so far accepted in postulating a rising temperature within the mostly solid earth. If the globe has grown up by the infall of planetesimals of minute diameters, its outer portion has always been cold. The initial state of the material assembling on it would be dust; mingling with water, the

dust would become mud; and, on being washed into shallow depressions, the mud would form continental or marine sedimentary deposits. Compacting and cementation would produce rock, but it would not be igneous or metamorphic rock unless buried to a depth within reach of high temperature. After it had been buried to that depth in a growing globe, it could not reappear at the surface except as a consequence of eruption.

The oldest rocks of which we have any knowledge are gneisses and schists, which may have originally been igneous or sedimentary, but which are now so altered by metamorphism at high temperature that their former state can not be recognized. They are associated with very large masses of intrusives of undoubted igneous origin. If regarded as crystallized planetesimal dust, these rocks can represent only the infalls of the latest few hundred million years plus additions by eruption from the deeper zones of the earth, according to the processes already sketched.

We are constrained to conclude that the external skin of the earth has been formed by igneous and metamorphic action. Advocates of a molten globe or molten outer shell will see in the crust the final result of a simple process of cooling. Consideration of the alternative view may indicate that the observed facts are consistent with the assumption of a process of fractional melting, intrusion, metamorphism, uplift, erosion, and exposure. Let us see.

There is little, if anything, in the constitution of the older terranes to suggest simplicity of development. They are commonly known as complexes, in recognition of the diversity of rock types and the intricacy of relations. They represent a very long history of repeated intrusion, metamorphism, and distortion, which is quite inconsistent with the classic hypothesis of a simple era of cooling and encrustation. If there ever had been such an era the process of cooling must have progressed to the establishment of a permanent crust, which would subsequently have been modified by long-continued and oft-repeated eruptions of igneous rock from beneath it. The Archean complex might represent such a crust, but the activity must long ago have died down, since at present there is essential solidity to a depth of 3,200 kilometers (2,000 miles). The fact is that the Tertiary and Quaternary have been periods of extremely active mountain growth and continental warping. Following an era of comparative inactivity during the later Mesozoic, the globe, with the exception of the Atlantic regions, has demonstrated remarkable capacity for intense activity. As Chamberlin has forcibly remarked, the earth is not in a stage of senility.

If, on the other hand, the earth be heated up from within, it should at least maintain its activity. The development of the asthenosphere, the growth of asthenoliths, and eruptions from the latter appear to be logical sequences. Repeated intrusion, uplift, and erosion would necessarily follow as local evidences of the internal activity. There would naturally be periodic changes, inherent in the complexity of the processes of heat generation and transfer, and yet the average increment and expenditure of energy would be so balanced as to show no appreciable change during recorded geologic history. This seems to be the fact.

Igneous processes being indicated as of general development in the formation of the crust of the earth, it is appropriate to consider how sufficient heat can be concentrated in the cool shell to effect melting.

In accordance with the evidence afforded by the basement complexes and by the local occurrences of eruptions during the eras of known geologic history, we regard the concentration of heat in the crust at any time as a local phenomenon, to be explained by local conditions. This being postulated, we may distinguish as causes of a rise in temperature at least three conditions: (1) the rise of igneous intrusions from the asthenosphere; (2) work done in shearing and folding; (3) chemical reactions with the release of heat energy. The citation of illustrations will serve to give each one of these its significance.

Great outflows of basalt, such as have occurred in India, South Africa, South America, and North America, are regarded as flowing from the basic magma of an asthenolith because their volume and content of latent energy are so great that concentration of the heat in the crust appears improbable. A cover of 30 miles or probably more than 30 miles in thickness seems imperatively required to hold the mass when molten. If, as seems practically demonstrated by seismic evidence, the bottoms of the ocean basins are floored with great thicknesses of similar lava flows, the depth of origin is probably deep in proportion as the volumes are great. Batholiths also presumably originate in the asthenosphere. Their masses are very large in some cases, and the differentiation of their constituents from the basaltic magma is best explained under conditions that exist beneath the outer shell. They are not always large, however, and the potency of gases in promoting solution of the granitic constituents suggests that they may melt, solidify, and melt again if arrested in course of their ascent through the crust. Their substance having been differentiated in an asthenolith and having risen in association with gases to an elevated position from which

escape was possible, they might penetrate only part way toward the surface. Cooling there and losing gases, they would crystallize as an intruded body, but might still have liquid roots that might serve as conduits for heat and a new gas supply. In course of time remelting might occur and the ascent of the magma be renewed. Thus, though the origin of a batholith is presumably in an asthenolith, it may pass through various changes in state and composition during its rise toward the surface. It is obvious that intrusions from the asthenosphere into the outer shell must localize large quantities of heat in the latter.

Strain melting is thought to occur quite commonly on major upthrust planes, or ramps. The work done is quantitatively adequate, the localization of the energy is favorable, and the fact that the otherwise insuperable friction is overcome indicates the development of a lubricating film of magma. The volcanoes at the eastern base of the Sierra Nevada in California are significantly located and appropriately small in volume.[33] My studies of the tectonics of the Dead Sea have led me to attribute the basalt flows in that vicinity to strain melting on a large scale and under conditions of excessive pressure.[34]

The effects of chemical activity in producing high temperatures are well known in mines, at the shallow depths where oxidation is an active process. Their relation to hot springs is in some cases well established. Even voluminous accumulations of lava may be due to the combustion of juvenile gases, as has been shown by Day through his investigations of Kilauea.[35]

Of the three sources of heating in the outer shell, the first, by intrusion, is undoubtedly the most effective, the second decidedly less so and more narrowly localized, and the third comparatively very superficial.

To these three certain sources of heat sufficient to melt rocks of the skin we must add radioactivity, to which some would assign an important, if not predominant, rôle.[36] The efficiency of the radioactive minerals as sources of heat in the earth is still indeterminate. Whatever value it may ultimately be found to have will be an addition to the other sources of heat to which melting may certainly be ascribed.

It appears, then, that the outer shell of the earth, however formed originally, is now, after the lapse of hundreds of millions of years of

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[33] Adolph Knopf: A geological reconnaissance of the Inyo Range and the east side of the Sierra Nevada. U. S. Geol. Surv. Professional Paper 110, 1918.

[34] Bailey Willis: The Dead Sea trough, rift valley or ramp valley? Bull. Geol. Soc. Am., 1928.

[35] A. L. Day and E. S. Shepherd: Water and volcanic activity. Bull. Geol. Soc. Am., vol. 24, 1913, pp. 573-606.

[36] John Joly: The surface history of the earth, 1925.

modification, a complex of igneous rocks produced by eruption from deeper zones or by melting of its constituent rocks in consequence of local heating up.

We observe further that the two families of rocks of which it is composed, the granitic and the basaltic, form respectively the masses of the continents and ocean beds, and thus, returning to our first postulate, we may finally check the line of reasoning against some of the details of surface features.

Details of Ocean Beds and Continents

The ocean beds present rather smooth, long, and gentle slopes from broad submarine plateaus to greater deeps. The forms are similar to those of basaltic volcanoes and far-spreading lava flows, which are characteristically present in oceanic areas, so far as they rise above the waters, and may with some assurance be regarded as the prevailing formation beneath the waters. They must be indigenous, native to the regions in which they occur, and thus are the extruded magmas melted somewhere beneath the ocean floors. We may suppose them to have risen from a temporary position in the outer shell or to have come directly from an asthenolith situated in the asthenosphere.

The duration of the molten state of these magmas is a difficult question. We may postulate either that they are (1) permanently liquid within the earth, or (2) usually solid and only occasionally liquid, or (3) continuously solid during certain geologic periods and intermittently liquid during other epochs.

It was once regarded as beyond question that there is beneath the outer shell a liquid, molten globe, but the researches of Sir William Thompson and Sir George Darwin in the attractions of the tides showed that the globe as a whole must be solid.[37] These classic studies have been supplemented by the precise investigations of the tidal effects at Williams Bay, Wisconsin, by Michelson,[38] who determined that in that region the "tides in the actual earth are 0.310 of what they would be if the earth were fluid. The extensive researches of Chamberlin and his colleagues into the tidal responses of the globe and their investigations of the transmission of seismic waves have led them to conclude that "the earth-body is essentially an elastico-rigid spheroid in which the molten and viscous

[37] Sir George Darwin: On stresses caused in the interior of the earth by the weight of continents and mountains. Proceedings Royal Society of London, vol. xxxii, 1881, pp. 432-435.

[38] A. A. Michelson and Henry G. Gale: The rigidity of the earth. Journal of Geology, vol. xxvii, 1919, pp. 585-601.

elements are so far subordinate that the larger problems of the earth-body are to be solved on the elastico-rigid basis."[39] The testimony of geologic stability which is found in the exceedingly slow, sometimes imperceptible, rate of change of physiographic and geographic features of the surface strongly supports the mathematical, physical argument. It would seem that the first proposition of permanent liquidity must be set aside.

The second postulate, that magmas may be usually solid and only occasionally liquid, raises questions of the conditions of freezing and remelting. We have tried to meet those questions in discussing autogenous dikes and asthenoliths and need not here review the subject. If that argument is valid, we may proceed on the understanding that we regard bodies of magma as temporary occurrences, in a geologic sense; that is to say, the molten state may be maintained for a geologic epoch or longer.

The third suggestion, that a greater degree of solidity has characterized some ages as compared with others, springs from the recognized fact that periods of inactivity of great duration have alternated with periods of marked activity through the earth's recorded history. The Present is part of an epoch of marked activity.

Combining the deductions regarding the second and third conditions, we frame the idea that during an epoch of marked activity of the internal forces the number and sizes of bodies of molten magma in the earth, and particularly in the asthenosphere, are relatively large.

We thus reach the question: What diameter and what thickness of magma gathered in an asthenolith are compatible with the observed facts of essential stability of the earth's major features and levels today?

If certain assumptions as to depth beneath the surface and viscosity of magma were made, the problem might be attacked mathematically, and it well may be. But the analysis is lacking, and *faut de mieux* we may ask the Earth herself.

Let us examine the earth's surface for evidence of the existence of active asthenoliths and measure such as we may find. Evidence of activity will be found in eruptions. An asthenolith, regarded as a blister beneath the earth's skin, must collapse if emptied or to the extent that its magma escapes. Hence it follows that an active asthenolith is to be recognized by actual or recent eruptive activity and by a depression in the surface of the globe.

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[39] T. C. Chamberlin: Study of fundamental problems of geology. Carnegie Yearbook No. 21, 1922, pp. 359-362.

Iddings supplies a map which brings out the general, well-known relations of volcanic activity to the deeps of the ocean basins.[40] Chamberlin made a contribution to the subject by causing Emmons to map the chief submarine concavities of the surface.[41] We there see that the concavities (which we interpret as collapsed asthenoliths) margin the continental masses and are widest and deepest where the volcanic ranges are highest. Some of them, however, border coasts where there is no volcanic activity, such as the eastern coast of North America, and require special consideration. If they represent asthenoliths, they are now dead and have been dead during the ages which have elapsed since the last eruptions in the given region; or, if they do not represent asthenoliths, there is some other condition which may produce great depressions.

Accepting as active asthenoliths the masses beneath those concavities that are related to volcanic chains on adjacent lands, we find that they are from 100 to 300 miles (160 to 480 kilometers) wide and often many hundred miles long. The question immediately presents itself: Could a molten body of these dimensions fail to betray itself by yielding in an obvious manner to the attraction of the moon? Would it not greatly affect the tides? However, when we recall that the dimensions are those of the Mediterranean Sea, which has a free water surface and yet is almost tideless, and that we are considering the effect of tidal attraction on a body of viscous magma under a heavy cover, it seems entirely possible that an active asthenolith of these dimensions may exist without obviously disturbing the stability of the surface. Even greater diameters appear possible, and we pass with confidence to such deeps as the Caribbean, the Gulf of Mexico, the eastern and western basins of the Mediterranean itself, and the component hollows that make up the depressed areas of the ocean basins.[42]

Where the supposed asthenoliths show evidences of vulcanism we may class them as more or less active. Where there are no such signs we may infer that they are now dead and inquire into their past history. Around their margins it may generally be observed that the basement rocks consist of igneous intrusives or extrusives. They constitute the

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[40] J. P. Iddings: The problem of vulcanism, 1914.

[41] T. C. Chamberlin and R. D. Salisbury: Geology, 1909, map, p. 586.

[42] Professors Michelson and Moulton, on being independently consulted, both expressed the opinion that the effect of an asthenolith of the dimensions indicated on the tidal responses of the earth could be detected only by sensitive apparatus placed over or in the immediate vicinity of the molten body. This appears to place the reaction beyond the possibility of geologic observation and to indicate that the present or past existence of asthenoliths is not incompatible with the degree of stability demonstrated by geologic processes.—B. W.

foundations of island chains and mountain ranges surrounding the depressions and testify to past activity.

The deeper portions of the ocean basins, including the great deeps and moderately deep hollows, thus seem reasonably attributable to the outflow of magma from asthenoliths, especially around the margins, in a manner that permitted the subsidence of the cover. If, in consequence of the subsidence, tension developed cracks on the under side in the central region and lava escaped directly upward, the depth of the basin was not modified, because the volume of the outflow and the resulting subsidence compensated one another. On the other hand, the lateral outflows piled up extruded masses around the margins and permitted subsidence. They are the volcanic ranges around the basins. They may constitute a major part of an Andean Cordillera or may lie beneath an ocean, causing wide shallows such as surround the Hawaiian Islands or occur over the mid-Atlantic ridges.

The volcanic forces are frequently competent to raise the vents high above sealevel. The occurrence of volcanoes that rise from the submarine ridges is a characteristic feature which has a genetic significance. The identity of the basic lavas with the basalt, which we regard as typical of the suboceanic shell, establishes their relation to a common source with the latter. They not only demonstrate the activity of the igneous masses we have identified as asthenoliths, but also locate those bodies beneath the oceans.

Let us now turn to that phase of the evidence which bears more directly on the building up of continental platforms, which, we may repeat, we regard as characteristically granitic in composition.

The Isthmian land that connects North and South America is a relatively recent development. Throughout the geologic ages preceding the Tertiary the oceanic currents appear to have flowed uninterruptedly from the Atlantic to the Pacific between the two continents. During the Tertiary the ridge was built up and the land barrier was eventually established as the latest contribution to the continental masses. The Isthmus of Panama appears to be the latest link forged in the chain. It lies between the Caribbean deep on the north and a pronounced branch of the Pacific deep on the south, in the locus of a submarine shallow between two asthenoliths; but the ridge rises above the waters. We learn from McDonald [43] that the igneous rocks comprise quartz diorites and granitic rocks, andesites, rhyolites, basalts, and mud-flows. The prevailing types are those of the granitic family. According to

[43] Donald F. McDonald: Geologic section of the Canal Zone. Bull. Geol. Soc. of Am., vol. 24, 1913, pp. 707-711.

Vogt, Bowen, and other petrologists, they are to be regarded as the acid differentiates from larger bodies of more basic magma, and, following the line of preceding postulates, we would regard those bodies as asthenoliths which were located beneath the adjacent deeps.

Thus the youngest element of the continental masses of North and South America appears to be so located and so constituted that it links the genetic process of continental growth with the evolution of suboceanic depressions.

Following up this line of evidence, we may note the additions which have been made to the continental masses during the late Paleozoic, Mesozoic, and Tertiary, in the form of large batholiths.

A very long line of batholithic intrusions occurs around the Pacific basin. The granite commonly intrudes sediments whose ages range from late Paleozoic to Miocene. Its masses are sometimes still covered by the metamorphics or are hidden by younger deposits of sedimentary or volcanic origin. There are interruptions of the granitic chain and some of them represent large gaps. Nevertheless, the long, simple coastline of North and South America is a succession of granite ribs. Tierra del Fuego,[44] Chile, Peru, Colombia, Mexico, California, Washington, British Columbia, and Alaska all are found to have had eruptive sequences in which granite was an early and very voluminous member, while the later eruptions were basic intrusives or extrusives ranging from andesite to basalt in character. The chronologic relations of the rock types suggest eruptions from the differentiated magmas of asthenoliths, which initially contained a relatively large proportion of the acid constituents.

Along the Asiatic and East Indian coasts of the Pacific the eruptivity has been similarly active during the same geologic periods, from late Paleozoic to the Present, and granitic rocks were among the earliest; but they are less conspicuous in volume and they are arranged at the surface according to a different plan. The very long batholiths, which are particularly characteristic of the North American coast region, are replaced in Japan by lenticular bodies that suggest enormous gash veins. They lie *en échelon* and indicate tensile strains due to shearing, as has been brought out by Tokuda.[45] The slender island arcs rarely exhibit true granite, though acid intrusives occur. Smith says:[46]

[44] L. C. Decius: Los Recursos Naturales de la Tierra del Fuego. Published by the Direccion General de los Territorios Nacionales, Argentina, 1916.

[45] S. Tokuda: On the echelon structure of the Japanese archipelagos. Japanese Jour. of Geol. and Geog., vol. v, 1926, pp. 41-76.

[46] Warren D. Smith: Geology and mineral resources of the Philippine Islands. Bureau of Science, Manila, 1924, p. 98.

"The parent magma of the Philippines was of such composition that the part which reached the surface produced an andesite or dacite; the portion which did not reach the surface cooled more slowly and became diorite, or quartz-diorite, or diorite-porphyry."

This is probably true in general of the islands that resemble the Philippines in mass, their very slenderness removing them in that respect from the category of continents, as does their more basic constitution. New Zealand, a larger land area, has a granitic batholith in its southern section, that is exposed in the southwestern region, which is known as Fiordland, and very probably extends under the extensive Otago Plateau, as was observed by Finlayson.[47]

The evidence that is thus too briefly reviewed appears to support the hypothesis that the continents bordering the Pacific basins have been built up on the Pacific side by eruptions from active asthenoliths situated beneath the adjacent parts of the ocean bed, and that the continental character of the land bodies has been more or less pronounced according as the volume of granitic differentiate was greater or smaller. These additions to the continents have been made chiefly during the post-Paleozoic ages and indicate clearly that the process of continental growth is still in progress.

The eruptive activity of the Atlantic basins contrasts with that of the Pacific in time, but not in kind. The youngest intrusions of granitic rocks in lands bordering the Atlantic are of late Paleozoic age and were associated with the Appalachian revolution. Elsewhere the batholiths, which are of general occurrence, are even older and most of them are Precambrian.

Beginning again with South America, we find the eastern coast region composed of Precambrian granites from the La Plata indentation to Guiana, thus extending the whole north-south dimension of the South Atlantic basins. On the eastern side of the same ocean, bordering the group of basins that lie east of the mid-Atlantic ridge, Africa presents a very similar structure.[48] The similarity extends to the form and constitutes the basic suggestion for the Wegner hypothesis of drifting continents. Without having purposed competition with that remarkable theory, an alternative is evident. Similar processes appear to have produced similar results in similar regions of the earth's crust during approximately the same periods of time.

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[47] —— Finlayson: Gold veins of Otago. New Zealand Geological Survey.

[48] Alex. L. Du Toit and F. R. C. Reed: A geological comparison of South America with South Africa. Carnegie Institution of Washington, Publication 381, 1927, map on page 116.

North America appears once to have had an eastern element which occupied a position east of the Appalachian Strait during Paleozoic time and disappeared during the Appalachian revolution. The extent of this land is of course conjectural, but the sediments derived from it in Cambrian and later periods, including the Carboniferous, were exceedingly siliceous and represent rocks of the granitic family.

From the Saint Lawrence to Greenland and Scotland we have great Precambrian batholiths dominating the structure of the ancient igneous complexes and forming the oldest masses of the continents. In Scandinavia and presumably beneath Russia we have the extension of the granitic masses that, joining with Asia, complete the group of continental bodies which distinguish the northern latitudes as the outer, lighter end of the planetary bolt which was shot from the sun.

Continental Welding

In passing from the individual, linear batholiths of the western coasts of the Americas to the wide continental areas of the northern continents we have wandered from the somewhat simple and obvious forms to the complex and obscure. We have also pushed the investigation back in time from the relatively near to the most remote ages we can recognize, and have thus lost that distinct geographic picture in which we may see the relations of the batholiths to their probable origins. Assuming that our interpretation of the simpler forms is correct—that is, that they were erupted from suboceanic asthenoliths, and also that the complex continental masses had similar origins—we shall do well to seek an example of less complex asembling of continental elements.

India appears to offer the desired illustration. The peninsula of India consists of Precambrian gneisses, granitoid rocks, and metamorphics which have been intruded by large bodies of granite. Exposed over very large areas, this fundamental complex extends far and wide beneath younger formations and may be regarded as constituting a continental element which is essentially coextensive with the Peninsula region. It lies between deep embayments of the Indian Ocean on two sides, and on the third side, the northern, it was formerly bounded by the strait that Suess called the Tethys, but which has now become the alluvial plain of the Ganges. North of the latter is a major element of Asia, the Tibetan Plateau, with its marginal range, the Himalayas.

The Peninsula continental element became welded to the Tibetan in consequence of the orogenic activity that raised the bottom of the Tethys strait and the adjacent zone of the Himalayas and established the land

connection. This occurred during the late Mesozoic and Tertiary and the movements may be regarded as still in progress. Outlines of the essential facts may be found in Medlicott's classic Geology of India and in Wadia's more modern summary.[49]

The process of welding comprised three major features: (*a*) The eruption of very large masses of granite into the zone of the Himalayas; (*b*) the extrusion of the vast volume of Deccan basalt in the northwestern part of the Peninsula; and (*c*) the compression of the zone that had been occupied by the Tethys, involving the folding of the strata previously deposited there. The eruptions of igneous rocks are assigned to the closing epochs of the Cretaceous period and the Eocene. The folding, upthrust, and outthrusting of the Himalayas was initiated toward the close of the Miocene and is still in progress.

Stepping back in geologic history, we may find in the Appalachian revolution a close parallel to the welding of India and Asia. The long zone of folded Paleozoic strata corresponds with the folded strata that accumulated in the Tethys. The remnant of the eastern continental element, Appalachia, which is now to be found in the Piedmont belt, the Blue Ridge, and the Smoky Mountains, has been pushed westward and welded to North America by processes essentially identical with those which have much more recently operated to unite the Indian element to the great Asiatic mass.

These two illustrations will suffice to recall to mind the well-known phenomena of the compression of geosynclines, which plays so large a part in the discussion of mountain-building. It can not well be divorced from the larger process of the welding of continents, of which it is an incident.

We are now prepared to consider some of the more complex continental assemblages.

North America consists of a number of bodies which have been distinguished as positive elements of the continental structure.[50] They are prevailingly granitic or gneissic in composition and are thus typically continental. Whatever their origin may have been, they have demonstrated a tendency to stand with their upper surfaces at a higher level

[49] H. B. Medlicott: A manual of the geology of India, vol. i, 1879, pp. xiii-xxiii.
G. N. Wadia: Geology of India for students, 1919.

[50] Bailey Willis: A theory of continental structure applied to North America. Bull. Geol. Soc. Am., vol. 18, 1907, pp. 389-412.
B. Willis and R. D. Salisbury: Outlines of geologic history, paleographic maps. University of Chicago Press, 1910.
Charles Schuchert: Paleography of North America. Bull. Geol. Soc. Am., vol. 20, 1908, pp. 427-605 (p. 464).

than that which was commonly assumed by their surroundings. They have therefore remained land areas when shallow seas pervaded the continental platform; or, if the continent as a whole was temporarily submerged, they were the first areas to emerge in the withdrawal of the waters. Thus their existence is demonstrated by the facts of stratigraphy and unconformity.

The positive elements of a continent are individual bodies that are set in a matrix, as it were, and the matrix has been designated as negative because the corresponding areas tend to subside. They have been called elements, as though they also were individual masses, but the word zones better describes their actual relation to the positive elements. They are zones which surround the latter. Holding that general relation of plan and tending to subside negatively rather than to rise positively, they have been covered by epicontinental seas and by sediments laid down in the waters. Moreover, they have zones of folding, and the resulting structural axes have conformed to the outlines of the positive elements that constituted the resisting rigid bodies. The basic structure of the continent is thus recorded structurally as well as stratigraphically.[51]

If we review the two historical cases of continental welding which have been cited, or others of similar character that might be, we find that there is great similarity of behavior with the positive and negative elements in a complex continent.

The Indian and Tibetan, the Appalachian and interior North America positive elements were separated by zones in which subsidence was the characteristic tendency, as it has been with the negative elements. The latter have persisted in the inherited or inherent tendency of their kind or situation. Following the history backward in the light of the historical facts, we may confidently postulate that North America and the other great continental complexes have been formed by the welding of positive elements in consequence of horizontal compression. The negative elements correspond with the welds. The positive and negative continental elements therefore make up the continents whose genesis and development we set out to trace.

Summary of Hypotheses

We may now sum up this presentation of facts, inferences, and assumptions in a form suitable for further investigation, somewhat as follows:

[51] Bailey Willis: Research in China. Vol. ii, systematic geology. Carnegie Institution Publication No. 54, 1907, pp. 115-117.

(*a*) In the body of the earth, and particularly in the asthenosphere, there have developed and are developing bodies of magma that have the form of blisters and to which we have given the name *asthenolith*.

(*b*) Asthenoliths develop by a process of gradual heating up and melting, favorable to their growth in volume and diameter, and also to the differentiation of more or less acid or basic facies of the magmas.

(*c*) The growth of an asthenolith, assuming the heat supply to be kept up, is limited by the strength of its cover, the rupture of which is the beginning of eruptions and collapses that constitute the final, though very prolonged, stage of its active existence.

(*d*) The conditions of gestation in an asthenolith are favorable for differentiation and stratification of the magma.

(*e*) Magmas erupted from an asthenolith may be very acid or ultra basic or of intermediate facies, according to the level from which they come or as they are more or less differentiated. Magmas reaching the surface from some active subterranean source may come from different asthenoliths, lying side by side or one above another or *en échelon* at different levels.

(*f*) Magmas may be erupted from the margins of an asthenolith or from a central region. In the former case the erupted magma will pile up on a neighboring zone and the central region will sink in. It will thus be brought into tension and will become a locus of eruption through radial dikes.

(*g*) Eruptions of basic magmas that reach the surface result in far-spreading flows and low relief, except when they build up volcanic cones. These are features of the oceanic areas.

(*h*) Eruptions of dioritic or granitic magmas from the margin of an asthenolith result in the linear batholiths of continental margins and the crescent-shaped arcs of island chains.

(*i*) Eruptions of granitic magmas from an asthenolith, presumably from the upper central region, may result in very extensive intrusions into the outer shell, such as occur in the Laurentian of Canada. The intruded mass and batholiths constitute a positive element of continental structure. Such an element has a habit of standing at a relatively high level.

(*j*) Positive elements have tended to develop in groups and are largest as well as most numerous in the so-called "Land Hemisphere."

(*k*) Between any two positive elements, where not too widely separated, there is a zone which has the habit of relative subsidence with reference to their levels. The zones of this character constitute the negative elements of the continents, the well-known geosynclines.

(*l*) The vertical movements of positive and negative continental elements have from time to time been interrupted by tangential compression, which has forced the positive elements together, folded the sedimentary strata of the geosynclines, and welded the positive and negative elements into a continental complex.

Residual Problems

GENERAL STATEMENT

Any attempt to solve the problem of continental genesis must involve the related problem of the origin of ocean basins, and we have not escaped the issue. In fact it has become apparent that the hypothetical asthenolith is the genetic element of an ocean basin and that continents are secondary growths of special composition. We have also suggested an explanation for the arcs which have recently been discussed among geologists as effects of thrusting only. But several questions remain untouched. Thus:

ISOSTASY

If the hypothesis of continental genesis here suggested be true, what balance may be struck between complete isostatic compensation, of the Hayford-Bowie type, and partial rigidity, of the Gilbert leaning?

PERMANENCE

In view of the igneous activity indicated in the asthenosphere, is it among the possibilities of earth history that the marginal ridge between two asthenoliths—a Panama, for example—might be melted down and a land connection severed? And how far could such an action go in reducing a continental mass?

STABILITY

On the other hand, what duration of stability is indicated as natural to the outer crust of the earth if the disturbing forces are dependent for effective action on recruits from the very slow accumulation of heat in the interior?

TANGENTIAL COMPRESSION

What forces that would result from the development of asthenoliths might operate in an appropriate manner and with sufficient power to produce the observed effects of folding, thrusting, and shearing that are characteristic of the continental masses?

Each of these and other questions will presumably receive attention in the course of time. The last named has claimed my thought in one form or another for many years, and the concept of an asthenolith has put it into an active state. It will find consideration as Metamorphic Orogeny.

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GEOLOGICAL HISTORY OF THE ANTILLEAN REGION[1]

VICE-PRESIDENTIAL ADDRESS BY CHARLES SCHUCHERT

(Read Before Section E December 28, 1928)

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INTRODUCTION

In selecting a subject for the address of the retiring Vice-President of Section E, I have taken the most interesting but least known portion of one in which I have been very much interested during the past twenty years and more, namely, the paleogeography of North America. The portion dealt with on this occasion is the known geological development of the greater Antillean region—that is, the seas and lands bounded

[1] Address as retiring Vice-President of Section E, American Association for the Advancement of Science.

Manuscript received by the Secretary of the Society January 3, 1929.

by the perimeters of the Gulf of Mexico and the Caribbean mediterranean.

The deciphering of the geological development of this greater Antillean region began with the versatile and philosophical Alexander von Humboldt. In June, 1799, he and the botanist Bonpland set out for Central and South America to study their physical geography and tropical botany. Humboldt first studied Venezuela and the Orinoco country, and later traveled more than a year in Cuba. After visiting western South America, he devoted the year 1803 to Central America. True to his training, Humboldt was an ardent Wernerian, and yet the leading student of volcanoes of his time. His most valuable results, however, are his geographic descriptions.

The geographic and geologic literature of the greater Antillean region is very voluminous, embracing the results of a host of workers, widely scattered in several languages. It is, indeed, altogether too extensive to be presented in brief form. The first important work on the stratigraphy and structure of the Greater Antilles is the report on the "Geology of Jamaica," by James G. Sawkins and his English associates, published in 1869. But the father of Antillean geology is undoubtedly Robert T. Hill, whose work in Panama, Jamaica, Cuba, and the Lesser Antilles forms the broad foundation on which all subsequent work must be built. The stratigraphic succession, and especially the marine faunal correlation from place to place, have been worked out more recently by T. Wayland Vaughan and his associates; another important contributor along these lines is Carlotta J. Maury. Voluminous additional paleontologic work is by Gilbert D. Harris and students trained by him. Our knowledge of Haiti we owe to W. P. Woodring and C. Wythe Cooke; that of Porto Rico to Charles P. Berkey and his coworkers of the New York Academy of Sciences; while the intricate problem of the coral islands, as seen in the Lesser Antilles, is ably presented by W. M. Davis in two recent books.

The Grander geological Features

Before turning to the detailed geology of this part of the world, it will be well to take a rapid look at the more general geology of the lands bounding the Gulf of Mexico and the Caribbean mediterranean. The clearly dated geologic history of the Greater Antilles is more especially of Cretaceous and Cenozoic times and only in western Cuba are there fossiliferous strata of Middle and Upper Jurassic ages. Beneath the latter, however, there is a deformed and metamorphosed basement, usually ascribed to the Paleozoic, which, on the basis of Central American history, should be of Permian and Carboniferous formations.

By general assent the Greater Antilles include Cuba, Jamaica, Haiti-San Domingo, Porto Rico, and the Virgin Islands. Cuba is clearly the oldest of the Antillean islands, already in existence in Paleozoic time. The other islands begin with volcanics, most of which appear to be of Upper Cretaceous time, but those in Porto Rico are of Lower Cretaceous age; all seem to lie upon a Paleozoic foundation. To the east of the Virgins are other limestone-capped islands, which are often also included in the Greater Antillean arc. Probably all of these northeastern Windward Islands are submarine volcanic growths of either late Cretaceous or early Cenozoic time, which have risen into lands at different times, been beveled across, then subsided deeply and accumulated a thick cap of limestones. All of the northern States bordering the Gulf of Mexico are also of Cretaceous and Cenozoic times and nearly all of eastern Mexico as well.

Central America, however, has an ancient core of deformed Precambrian crystallines and metamorphics which are well exposed in Honduras, southern Guatemala and Chiapas, and Oaxaca. This old protaxis disappears beneath the Mesozoic covering strata of southwestern Mexico. The Central American part of this protaxis trends east and west and is slightly curved to the south. It is widely overlapped on the north flank by Upper Carboniferous, Permian, Cretaceous, and Cenozoic formations, but on its southern side it is questionable if there ever were marine overlaps older than the Cenozoic. On the other hand, there was no volcanic Costa Rica and Panama apparently before Cretaceous time.

The northern area of South America in Venezuela and Colombia is also very largely composed of Cretaceous and Cenozoic formations, and while there are older ones in the mountain cores of these republics, none appear to go back of the Middle Devonian. These fossiliferous Paleozoic strata, however, rest on an older foundation that apparently is of Proterozoic time. Much of the northern borderland is now foundered into the depths of the Caribbean Sea, and the island of Barbados is its most northeasterly outpost. Tobago and northern Trinidad are other portions of this foundered borderland, which has been called Paria by Guppy.

This much-generalized account of the broader geology of the Central American-Antillean lands seems to bring out the fact that in late Proterozoic time the central Cordillera of western North America ended before attaining Oaxaca. Here another ancient protaxis appears with a northwest-southeast strike, but soon changes its course to one with a nearly east and west direction but convex to the south, and so continues through Honduras and apparently across the Caribbean Sea into Jamaica and possibly even beyond Haiti and Porto Rico. To the east of Haiti

the old protaxis subsides more and more and is covered with late Mesozoic and early Cenozoic volcanics.

Appearance of the Gulf of Mexico

Immediately to the north of this Central American-Antillean protaxis there lies a folded foreland that was much the widest across Cuba, and beyond it occurs what Suess has called the "Gulf of Mexico plate." This "plate" of nearly horizontal strata also includes the States bordering the Gulf of Mexico from Texas on the west to Florida on the east, and the latter part of the plate appears to have continued unbroken into the Bahama banks. During Paleozoic time this foreland plate subsided very little, even though the waters of the Atlantic Ocean extended across it, as shallow seas, to enter the geosynclines of Mexico and Appalachis. Finally, in the Middle Jurassic, there began in the northern hemisphere a great oceanic transgression, and in keeping with it, first Mexico and then the Gulf of Mexico began to subside, though most of the present form of the Gulf came with the late Cretaceous. Its greater depth, on the other hand, was developed especially during the Cretaceous and Eocene, with further deepening during Oligocene and Pliocene times. Even now the bottom of the Gulf of Mexico is not creased with folds nor much disfigured by normal faulting as is that of the Caribbean Sea. On all sides it is a gradually deepening basin, going down to over 12,000 feet, except in the east, where it is deformed by upfaulted Yucatan and the adjacent downfaulted Yucatan straits; both blocks are tilted to the west.

Caribbean Mediterranean

To the south of the Central American-Antillean protaxis the structural condition of the Caribbean mediterranean is very different. Here the Antillean borderland fronting the Caribbean Sea was always narrow and much of it has sunk into the abyss. The Caribbean waterway is now an abyssal and overdeepened one, but it appears to have had at all times depths greater than 10,000 feet, and is regarded by Suess as the western end of his Tethyian mediterranean. It differs from the Gulf of Mexico in not only being a vastly older and far more complex basin, situated between two continents, but also being greater in area and depth. Furthermore, its bottom shows northeast-southwest trending folds and troughs; and, in addition, it consists of two basins, a greater western and more folded one, with depths down to 14,100 feet, ending south of Haiti and Porto Rico in a supplementary fault-trough 17,100 feet deep, and a smaller but still deeper eastern and less folded trough, the Tanner Deep, with a maximum depth of over 17,000 feet. On the

other hand, in Cenozoic time most of the Parian borderland of South America was also downfaulted to depths ranging to nearly 17,000 feet, and much of western Antillea was faulted into the abyss during the Pliocene, changing a former structural synclinal valley here into the long and narrow Bartlett Deep, with present depths of over 19,200 feet. Farther north other parts of Antillea were downfaulted into a less deep basin, the Antillean Sea, which goes down, however, to nearly 15,000 feet.

Costa Rica-Panama Land-Bridge

Now the question arises, When was the ancient Caribbean opening into the Pacific closed by the land-bridge of Panama and Costa Rica that now unites South and North America? The direct evidence of the oldest volcanics in Panama shows that they are unconformably overlain by late Eocene faunas (Claibornian), and accordingly this basement is usually assigned to the early Eocene. On the basis of the late Mesozoic faunas, however, the California ones are seen to be so different from those of the same age in Mexico and the Gulf States as to support the conclusion that the land-bridge was more or less completed during Lower and Upper Cretaceous time. Its formation appears to have been started by the late Jurassic crustal movements, which developed here a submarine ridge that was studded by volcanoes. Previous to the late Jurassic, however, the Caribbean is believed to have been widely open into the Pacific.

The early Cenozoic stratigraphy of southern Central America and that of California and the West Indies region is everywhere so much alike that it is plain that the Costa Rican portal was again more or less widely open as a shallow sea, beginning with the Upper Eocene (Claibornian) and ceasing with the close of Lower Miocene time.[2] Since then elevation has here dominated over subsidence and the Costa Rican-Panama portal has remained closed. However, another but short-lived marine portal came into existence, this time to the north of Central

[2] Since this was written, Doctor Bruce L. Clark has told the author that the Oligocene faunas of the West Coast are totally different from those of the Antillean region. From this he concludes that there was no marine portal across Panama-Costa Rica during most of Oligocene time, and in this he has the support not only of Doctor Maury but of the author as well, since the latter, on reinvestigating the stratigraphic record, finds in the Panama-Costa Rica region no clear evidence of Oligocene formations until the close of this epoch. On the other hand, the mammal evidence is said to call for a complete absence of a land-bridge between North and South America until late Miocene time, when there was marked interchange of these animals. In order to harmonize these conflicting viewpoints, it will be necessary to find an explanation of why there was no Oligocene interchange of mammals between North and South America, and likewise why none of the northern ones got into Central America, since between these areas there appears to have been not only a continuous land but a wide one as well.

America across the Isthmus of Tehuantepec. It was certainly open during early Pliocene time and probably also during the late Miocene, permitting the marine faunas of the Gulf of Mexico to spread west and thence north into southern California as far as Carrizo Creek, where Atlantic corals and mollusks are known.

Central American-Antillean Land-Bridge

Previous to the late Eocene, and apparently back into Proterozoic time, it is certain that Central America connected widely across the Honduran-Nicaraguan banks with Jamaica and Haiti-San Domingo. It was then easy for the floras and faunas of Central America to spread into the Great Antilles. During all of Eocene and most of Miocene time, however, the South American connection was severed by a shallow sea across Panama-Costa Rica. To the north of Nicaragua, however, there was during this time continuous land into North America. On the other hand, late in the Miocene and during early Pliocene time the Tehuantepec portal came into existence, breaking this northern connection and stopping any South American migrants during this interval from getting into North America; but the waves of South American organisms could still spread to a limited extent into the Greater Antilles. With the Pliocene the Antilles were completely separated into their present entities, while South and North America could freely interchange their life forms.

The Caribbean volcanic Arc

In the east the Caribbean Sea during Paleozoic and most of Mesozoic time appears to have been widely open to the Atlantic, but when the deeply submerged ridge came into existence on which the Lesser volcanic Antilles originated is not known. From this ridge there arose in the north, certainly as early as Eocene time, many submarine volcanoes that made islands extending to Marie Galante in the south. This crescent of volcanoes is convex toward the Atlantic, and the completed series appears to have spread from north to south, with the Grenadines certainly the youngest of the series. There is, however, no direct geologic or submarine evidence to prove that the Caribbees at any time were a continuous land-bridge connecting South America with the Greater Antilles, as inferred by some zoogeographers. In the south these volcanoes are perched on the top of the subsided Parian borderland, and in the north they are parasitic growths on the western side of the older or Windward volcanoes, now covered by limestones and continuing the Cenozoic stratigraphy of the Greater Antillean series.

Barbados

The geology of Barbados is well known through the work of English naturalists, and it is doubly interesting since the island is covered by 350 feet of unmistakable oceanic deposits. Barbados lies in a hinge, or very mobile area, between the continent of South America and the Caribbean abyss, and the oceanic deposits of the island include even Red Clay, giving good ground for holding that the subsidence may have been to a depth of 10,000 to 12,000 feet. The series begins with shallow-water deposits, followed by the oceanic series of Globigerina and radiolarian oozes, and finally by Red Clay, and these are overlain first by shallower-water foraminiferal ooze and then by coral-reef rock. In addition, the oceanic Echini confirm the depth at which the oozes formed. This great subsidence, if such it actually is, took place essentially during Miocene time, and in the Pliocene Barbados rose again into shallow waters.

Vaughan thinks the subsidence may have been to about 5,000 feet. On the other hand, T. C. Chamberlin [3] advances the "alternative assumption that the benthos life and correlated conditions were carried up to unusual levels by upwelling currents about the island after it reached the stage of moderate submersion." The carrying "up to unusual levels by upwelling currents" is possible, for such occurrences are known in the present Pacific off South America; but one wonders if the abyssal Echini could have lived in "moderate depths."

For the present the conclusion appears warranted that Barbados and the whole of the north margin of Paria during the Miocene had sunk to a depth of at least 5,000 feet, and that Barbados rose a similar amount during the Pliocene, and 1,100 feet higher during the Pleistocene, this being the present highest stand of the island. That Paria was very mobile in the Miocene is attested by the 14,000 feet of strata of that age in Trinidad and northen Venezuela.

The Bahamas

In speaking of the flat Gulf of Mexico plate, it was said that the Bahamas were but a continuation of Florida. It may be added that the southeastern Bahamas, and those of the medial region facing the Atlantic as well, appear to be volcanic additions now covered deeply with limestone deposits. Their submarine slopes show this, since they are much like those of the Bermudas, which have proved to be limestone

[3] Jour. Geol., vol. 22, 1914, pp. 141-143.

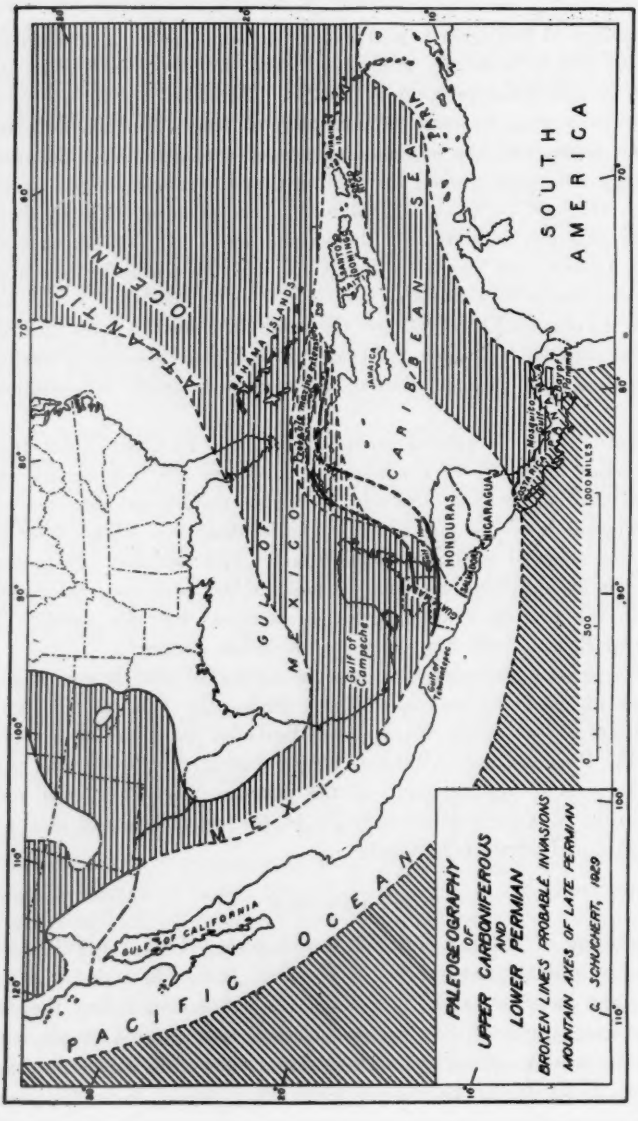

FIGURE 1.—*Paleogeography of the Central American-Antillean Region in Upper Carboniferous and Lower Permian Time*

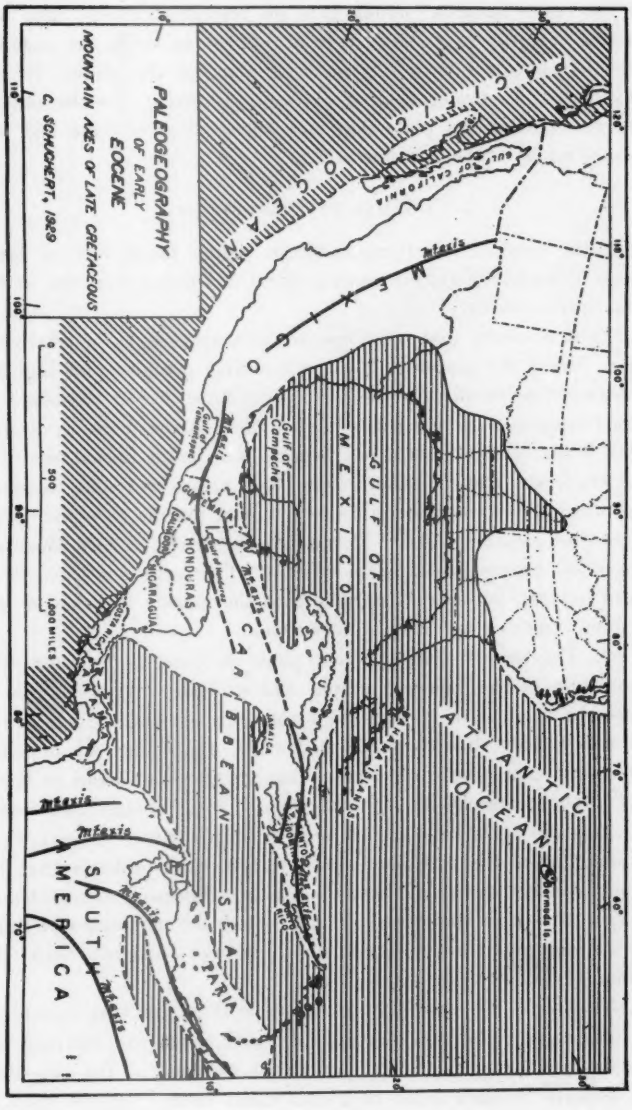

FIGURE 2.—*Paleogeography of the Central American-Antillean Region in Early Eocene Time.*
Costa Rica was submerged in Eocene Time

caps on a subsided volcano that also grew up from the ocean bottom. If the outer Bahama islands have no volcanic bottoms, then we must assume that the steep and irregular submarine slopes are organic reef-growths on this now deeply subsided part of the plate. Of the two hypotheses, we prefer that of volcanic addition. On the other hand, the Florida-Bahama plate does not appear ever to have had dry-land connection with the Antilles.

Times of Diastrophism

In the Central American-Antillean region there were at least four times of major mountain-making, three of folding, and one of faulting with local folding.

(1) The oldest and most obscure one appears to be of Proterozoic time. Here the basement rocks are largely granites and highly metamorphosed sedimentaries that were peneplained before the late Paleozoic seas transgressed across them. When the marine invasion of Paleozoic time began is not known, but beneath the dated formations of Upper Carboniferous and Permian times there are others some thousands of feet thick, and it may therefore well be that marine Devonian is present, as is often assumed. As no Devonian is known in eastern Mexico, where the oldest Paleozoic strata are of Lower Carboniferous time, it appears more natural, however, to assume that the marine invasion of northern Central America was also of this time.

(2) The second orogeny took place in Central America after the deposition of the Lower Permian and evidently in the middle of late Permian time, since no marine formations of Triassic age are known anywhere other than in northern Mexico, where they are of the Upper Triassic. It is also fairly certain that orogeny took place in late Paleozoic time in western and central Cuba. Even though these mountains of Cuba can not now be seen to connect with Central America due to the inbreaking of the Antillean sea, yet it appears probable that they attended southwest connecting with the late Paleozoic east-west mountain ranges of British Honduras. Farther south the mountains of Guatemala and Honduras extended across the Honduran-Jamaican banks into the island of Jamaica (see figure 1).

(3) Late in Cretaceous time began the third and best known orogenic deformation. This was of great strength, with the foldings very extended and along much the same lines as those of the late Paleozoic. It appears to have come to a conclusion before middle Eocene time. On the other hand, it is very probable that the mountain ranges of

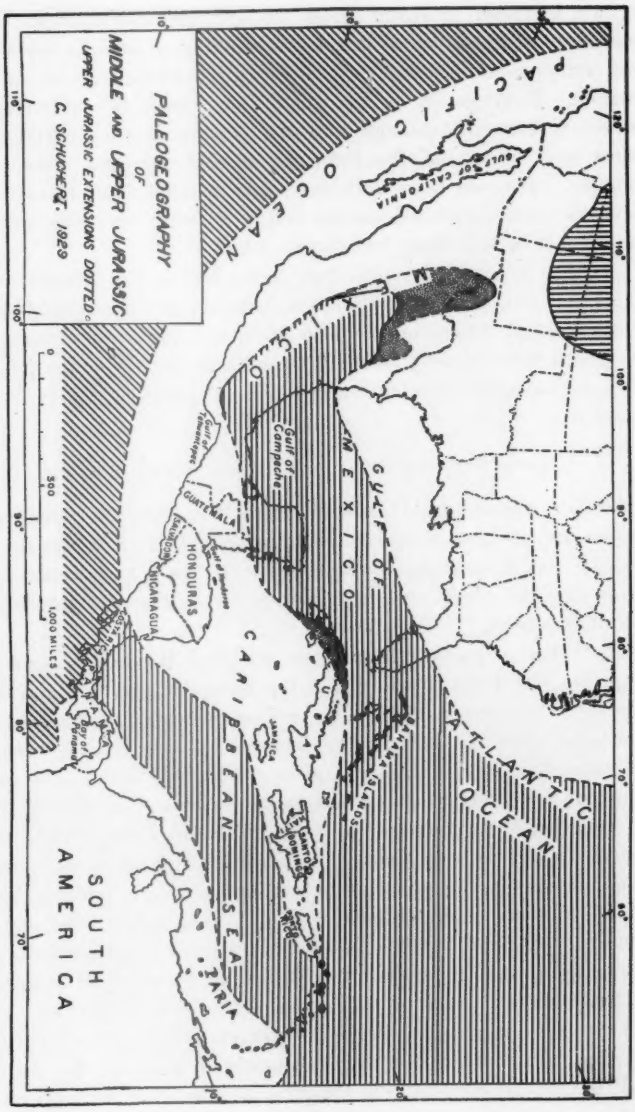

FIGURE 3.—*Paleogeography of the Central American-Antillean Region in Middle and Upper Jurassic Time*

British Honduras now made the dominant anticlinorium, which appears to have extended unbroken across the Antillean Sea through the Caymans into southeastern Cuba, thence striking diagonally across Haiti-San Domingo into Porto Rico, and finally terminating in the Virgin Islands. It is convex to the north. Another, but subsidiary, anticlinorium extended through southern Guatemala into northern Honduras and across the Honduran banks, but may not have attained Jamaica. Between these anticlinoria lay a valley that during the late Cenozoic subsided beneath the sea and in Pliocene time was faulted into the present Bartlett Deep (see figures 2 and 9).

(4) The fourth diastrophic time began late in the Miocene and was of greatest force during the Pliocene, bringing on the present high stand of the Central American-Antillean lands and the overdeepening of the Caribbean Sea. These crustal movements were mainly of the epeirogenic kind, very extensive blockfaultings with local compensating foldings (see figure 9).

Long Separation of North and South America

About a century ago Humboldt taught that "the two American continents are practically dominated by a continuous Cordilleran system, running like a backbone through South, Central, and North America, connecting the whole western border of the hemisphere into one great mountain system."[4]

About half a century later Suess modified Humboldt's view of the American Cordillera, holding that the mountain chains of Mexico run into those of Oaxaca, and there, turning east through Guatemala and Honduras, continue through the Greater Antilles, finally swing south with the strike of the Lesser Antilles, and are joined to the east-west ranges of Venezuela, which are but a spur of the Andean system. Sapper, on the other hand, between the years 1894 and 1905, showed that the mountains of northern Central America trend mainly east and west, while those of southern Central America are much younger and of a totally different origin, namely, volcanic. Hill, better than anyone before him, brings out the fact that the north-south trending Rocky Mountains cease in the "great scarp" of Mexico, to the north of Tehuantepec; that the similarly striking Andes terminate in northwestern Colombia and eastern Panama; and that all the structure lines of northern Central America, the Greater Antilles, the Caribbean Sea, and the north coast of Venezuela are transverse to the great northern and southern chains of

[4] Hill, 1898, pp. 158-161.

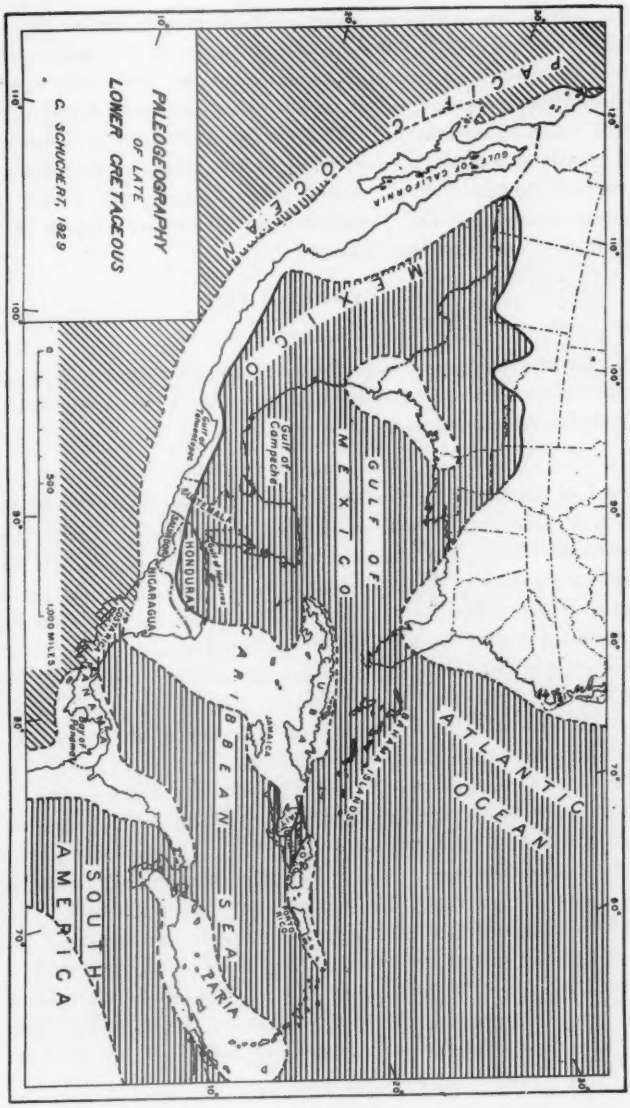

FIGURE 4.—*Paleogeography of the Central American-Antillean Region in Late Lower Cretaceous Time*

mountains, since their average strike is east and west. This great orogenic system, which Hill calls the Antillean system, makes the highland frame for the ancient Caribbean mediterranean on the north and south. The reason why this east-west trending has not been fully appreciated earlier, Hill states, is due "to the overwhelming proportions of the adjacent volcanic mountains." These latter developed in Cenozoic time "diagonally across the western ends of the east and west folds of the Caribbean configurations," in one series fringing the Pacific side of Chiapas, Guatemala, and Honduras, and in another western Nicaragua and all of Costa Rica and Panama.

PALEOGEOGRAPHY

GENERAL STATEMENT

With this presentation of the broader geological facts and conclusions, we may turn now to the paleogeography of the Central American-Antillean region and illustrate it on nine maps.

LATE PALEOZOIC TIME

Back of the Upper Carboniferous, the paleogeography of the Antillean region is obscure and will be considered at another time. Figure 1 shows that in the late Paleozoic the dry land of the North American continent appears to diminish into Mexico, and then turns east through Central America and the Greater Antilles at least as far as Porto Rico. It should, however, be kept clearly in mind that it is only since Cretaceous times that the Gulf of Mexico has attained its present great size and depth. Accordingly, in Paleozoic time the southern part of the North American platform was broadly rounded and bounded on the south by a mountain range that terminated eastwardly in the Antillean peninsula. Over this part of the platform the Atlantic Ocean spread shallow-water seas from time to time, but to the south of the mountain front lay the deep Pacific Ocean and the Caribbean mediterranean. South of the latter waterway was the Parian borderland of South America. There was then no Costa Rica-Panama and Lesser Antilles, and Florida and the Bahamas were of the flat-lying plate or foreland of Antillea. After Lower Permian time the whole of the Central American-Antillean folded land was again in the throes of decided mountain-making whose trends were in general east-west, but curved to the south. The known axes of these mountains are shown diagrammatically on the map.

JURASSIC TIME (FIGURE 3)

Following the Upper Permian orogeny there was little change in the geography of the Antillean region, other than in its topography, during

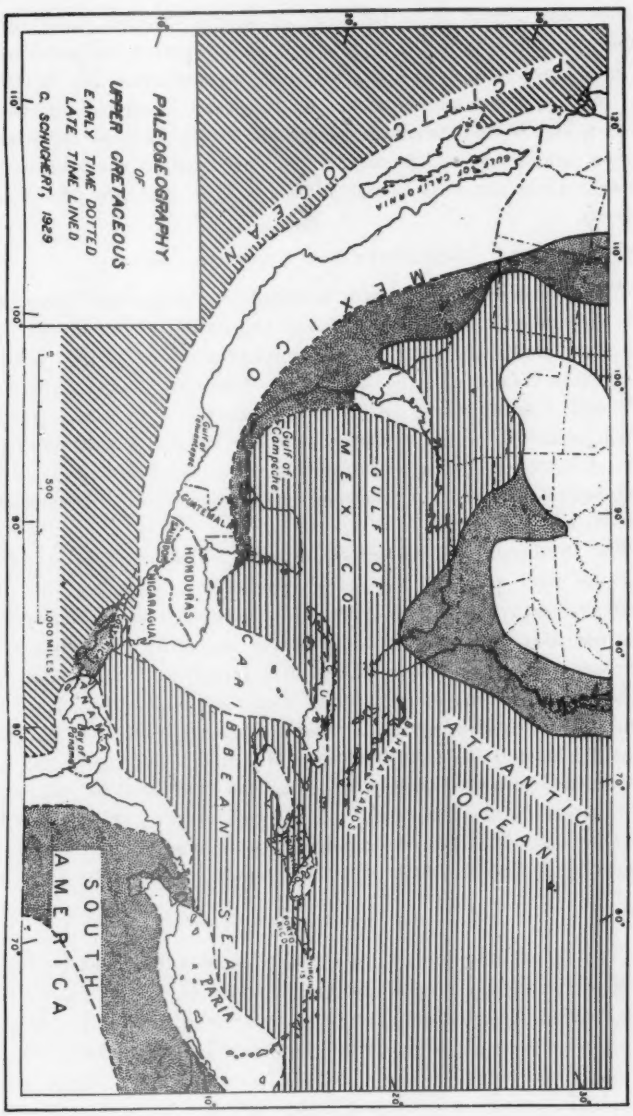

FIGURE 5.—*Paleogeography of the Central American-Antillean Region in Upper Cretaceous Time*

the whole of Triassic time. Early in the Jurassic, however, Atlantic waters were again invading most of eastern Mexico more and more widely, and finally, in the middle part of this period, the same sea began to spread across western Cuba, attaining its maximum late in the Jurassic, both in Cuba and Mexico. At this time or shortly afterward the eastern end of the Antillean geanticline began to grow submarine volcanoes, and more and more of them developed to the east with time, rearing their cones as island masses. They are now the Windward Islands.

CRETACEOUS TIME (FIGURES 4 and 5)

With the early Cretaceous a tremendous change was inaugurated by the widespread and deep subsidence, beginning in the western part of the Gulf of Mexico plate and in consequence inundating widely most of Mexico, Texas, and the northern portions of Central America. At this time also appeared for the first time the Venezuelan geosyncline, which connected in the southwest with the far greater and older Andean one. Closure of the Caribbean opening into the Pacific appears to have been begun early in the Cretaceous by the elevation of a submarine ridge replete with volcanoes.

The Cretaceous flood attained its greatest spread in the north during the later part of the period (figure 5), spreading far through western North America, over the Gulf border States as far as Illinois, and narrowly along the Atlantic border as far as Massachusetts. The Cretaceous flood also spread widely over the area of the Greater Antilles, especially in Cuba, Jamaica, San Domingo, and Porto Rico, and in South America the earlier inundation was maintained. At the same time the western side of the Rocky Mountains was rising and pushing the marine invasion farther to the east, as is attested by emergence not only in the United States, but all through western Mexico and Central America as well. The Costa Rica-Panama land-bridge may have been completed before the close of the Cretaceous.

EARLY EOCENE TIME (FIGURE 2)

Long before the close of the Cretaceous, mountain-making had begun in Mexico, and later crustal folding and elevation became general throughout Central America and the Greater Antilles, out to the eastern end of the Antillean arc. This dominant anticlinorium, which is curved to the north, extended through British Honduras and thence across the Caymans through southeastern Cuba, striking diagonally over San Domingo through medial Porto Rico and the Virgin Islands; farther east

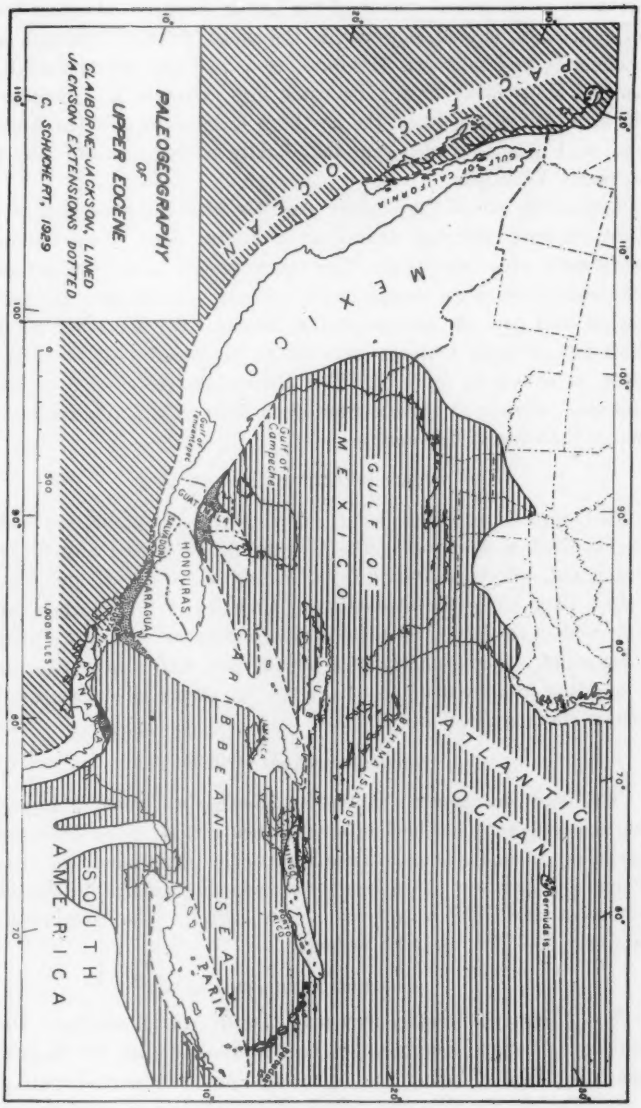

FIGURE 6.—*Paleogeography of the Central American-Antillean Region in Upper Eocene Time.*
In Jackson Time Costa Rica appears to have been all land

was rising a submerged ridge that was studded with volcanoes, now the northern or limestone islands of the Lesser Antilles. Another but lesser anticlinorium, curved, however, to the south, extended through southern Guatemala and northern Honduras and died out across the Honduran banks. Many other Laramides came into existence in Colombia during the late Cretaceous, being the northern terminations of the Andean system, with a northeastern spur that finally strikes east and west through northern Venezuela.

Apparently all of the Greater Antilles with the exception of western Jamaica were emergent during early Eocene time, when the Laramide movements were completed. The same appears to have been true of the Panama land-bridge, though much volcanic activity was general to this region well past the middle of the Eocene. On the other hand, Costa Rica and western Panama were under the sea during most of Eocene time, as shown in figure 6. The Bermudas are believed to have been emergent islands in Eocene time, with their volcanic activity exhausted before the close of this epoch.

UPPER EOCENE TIME (FIGURE 6)

In Upper Eocene time, when submergence was again very widespread in the Gulf border States, the Greater Antilles were also more or less inundated, affecting Jamaica, Cuba, and Haiti most, and Porto Rico only a little along the south shore. Colombia and Venezuela were likewise widely in flood, and most of Costa Rica as well, but Panama only marginally. Barbados was also submerged, and apparently all of the submarine volcanoes of the Caribbee arc north of Saint Vincent had grown above sealevel into islands.

OLIGOCENE TIME (FIGURE 7)

The flood inaugurated in the late Eocene was most widespread during the Oligocene in the Greater Antilles and northern Guatemala, and especially so in Cuba and Jamaica. On the other hand, the Costa Rica-Panama region was again land (see footnote page 341). Barbados was emergent and Florida appears as an island. The Bermudas, on the contrary, had gone beneath sealevel.

MIOCENE TIME (FIGURE 8)

The Oligocene flood is continued locally, as in northern Guatemala and in Haiti-San Domingo, into Lower Miocene time, but in general this epoch is a time of emergence, becoming more and more so until a climax is attained in the Pliocene. Costa Rica is again completely submerged in the early Miocene, but in the middle portion of this epoch becomes

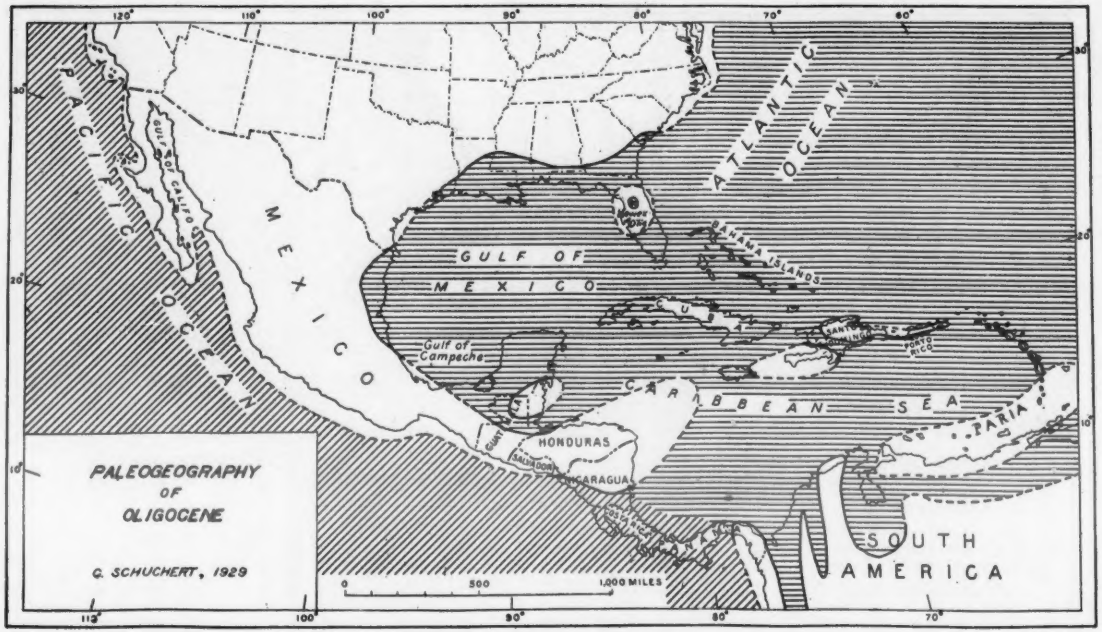

FIGURE 7.—*Paleogeography of the Central American-Antillean Region in Oligocene Time.*
Costa Rica-Panama should all be land.

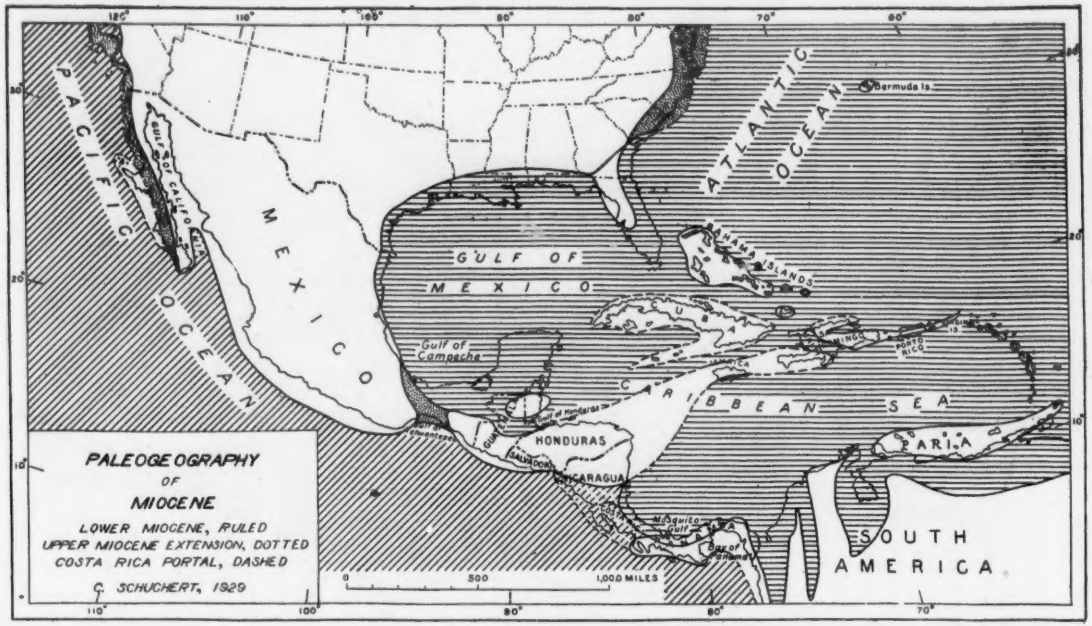

FIGURE 8.—*Paleogeography of the Central American-Antillean Region in Miocene Time.*
Costa Rica was under the sea during Lower and Middle Miocene Time

emergent, after which time only the Caribbean shore of the entire connecting land is under water. Northern South America is still widely submerged in Miocene times, when very thick clastic formations were laid down. Barbados may have gone down 5,000 to 10,000 feet, and in keeping with this great subsidence is the very great loading of Paria with detritus. Florida has now made its appearance as a peninsula. The Bahamas may have been above sealevel in late Miocene time, but more probably during the Pliocene. The Bermudas also appear to be emergent.

PLIOCENE TIME (FIGURE 9)

The Pliocene is almost everywhere the time of widest and highest emergence, and throughout Antillea there is tremendous fracturing and downfaulting. The old synclinal valley between Cuba and Jamaica, a sea since the Oligocene, is faulted into the Bartlett Deep, and Yucatan is deeply separated from Cuba, giving rise to the Antillean Sea. Eastern Honduras and Nicaragua and their banks are also let down to below sealevel, but Barbados has risen to near sealevel.

The marine overlaps of Pliocene time are small and marginal, the exception being the south side of the Gulf of Mexico, where these marine waters flood all of Yucatan, northern British Honduras, northern Guatemala, and the marginal States of southern Mexico north to Tampico; and probably during the late Miocene, but certainly in the early Pliocene, the Gulf of Mexico for the first time communicated freely with the Pacific Ocean through the Tehuantepec portal. After middle Pliocene time this portal also was closed and the whole of Central America has remained ever since an emergent and rising area. The Bermudas were submerged for at least a part of Pliocene time.

SUMMARY

This presentation of the geological history of the Antillean region, as stated before, is only along broader lines. Descriptively, vastly more knowledge is at hand, and this will later be presented in book form, but at present to show the garnered geography in more detail on a series of paleogeographic maps appears to be impossible, mainly for want of exact information in nearly all places, but on this occasion also because of the small-scale maps that must be used. However, many facts stand out clearly, and none more so than that the now very deeply sunken Gulf of Mexico, along with Florida and the Bahamas, are but the altered flat plate or foreland of the Greater Antilles and Central America, and that the two last-named lands make the very mobile southernmost frame of the North American continent. The great deepening of the Gulf

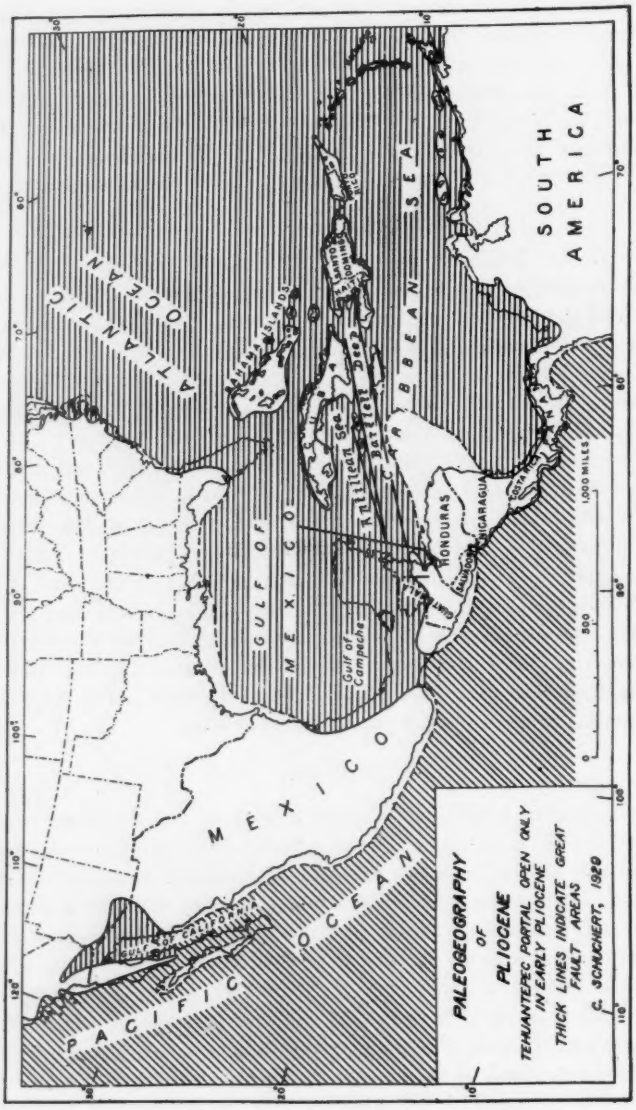

FIGURE 9.—*Paleogeography of the Central American-Antillean Region in Pliocene Time*

of Mexico took place during the Cretaceous, with further additions during the Oligocene and Pliocene, since which times the perimeter of this basin has risen a few hundred feet. The margining southern frame of the North American continent looks across the abyssal and ever-deepening Caribbean mediterranean to another mobile frame, namely, Paria, which makes the north borderland of South America and inside of which lies the normal and compensating Venezuelan geosyncline. On the other hand, the present northern extension of the Caribbean Sea was much overdeepened by the tremendous normal faulting of the Pliocene. During this epoch British Honduras and Yucatan, far to the north, were raised probably less than 1,000 feet and tilted to the west, while shortly to the east of them Antillea was let down many thousands of feet, bringing into existence the Antillean Sea south of central and western Cuba and overdeepening the Bartlett fault-trough between Cuba and Jamaica.

The Caribbean Sea on the west was completely barred from further connection with the Pacific by submarine volcanism that was intermittently active from late Cretaceous into Miocene times; but the younger volcanic additions throughout Central America appear to be very much greater in volume than the older ones that gave birth to Panama and Costa Rica. Finally, the beautiful string of Antillean pearls, the Caribbees, are also the product of Vulcan's fires, which all through Cenozoic times were intermittently stirred into activity.

As for the theory of the great westerly drifting of the two American continents, the speaker does not see the slightest evidence in the geological history of the Antilles to support this, nor is there any significant evidence to show that these continents have approached each other during geologic time more than a few tens of miles.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 40, PP. 361-384 JUNE 30, 1929

SOME HURONIAN PROBLEMS[1]

BY ANDREW C. LAWSON

(*Presented before the Society December 27, 1928*)

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AGE OF THE KILLARNEY GRANITE

INTRODUCTION

In 1916 I attempted[2] a correlation of the pre-Cambrian of the various districts that had been studied between Rainy Lake and the Adirondacks on the basis of the hypothesis that throughout this region there had been two, and only two, distinct periods of granitic irruption in the earth's crust.[3] For the earlier of these two periods the term "Laurentian" was retained, in accordance with long usage, and the later was called the "Algoman," a term which since has been widely adopted. The two plutonic upheavals are widely separated in time.

The Huronian rocks rest on the peneplained surface of the Laurentian granite and are cut by the Algoman granite. The Algoman granite was in turn deeply eroded and certainly peneplained before the deposition of the Animikie rocks of Thunder Bay. This alternation of granitic invasions and peneplanations, if general throughout the region referred to, affords a splendid basis of correlation. It was with some concern,

[1] Manuscript received by the Secretary of the Society January 25, 1929.

[2] The correlation of the pre-Cambrian of the region of the Great Lakes. Bull. Dept. Geol., U. C., vol. 10, no. 1, 1916.

[3] By this is meant irruption which produced granite still remaining to us as mappable structural constituents of the earth's crust. Earlier granites may have existed, but have wholly vanished. The "redrock" of the Keweenawan was excluded as a local product of migmatization.

therefore, that I noted the growth of doubt as to the validity of the hypothesis of two, and only two, periods of granitic irruption in this region. Collins and Quirke, in their studies of the Killarney granite and its equivalents (Cutler, etcetera), found that it cut both the Cobalt series and certain diabase dikes which traversed the Cobalt and Bruce series on the north side of Lake Huron. The Cobalt series was considered the equivalent of the Animikie of Thunder Bay and the diabase dikes were correlated with the Keweenawan. On the basis of these two correlations, it seemed clear that the Killarney granite must be Keweenawan or post-Keweenawan in age, and therefore much later than the Algoman granite, thus overthrowing the hypothesis of two, and only two, pre-Cambrian granitic periods.

But both the correlation of the Cobalt series with the Animikie of Thunder Bay and the diabase dikes with the Keweenawan are hypothetical, and, although I once accepted the equivalence of Cobalt and Animikie, it now seems to me that neither of the two hypotheses has as much inherent probability as that of two, and only two, granitic periods. In my correlation paper of 1916 I tabulated the geological sequence in fifteen districts, extending from Rainy Lake to the Adirondacks. In thirteen of these, granites of two ages appear in the tabulation. In 1915 Allen and Barrett[4] had recognized a second, or Huronian, granite in eight districts, three of which I incorporated in my own tabulation. In 1914 Miller and Knight[5] tabulated the pre-Cambrian sequence in nineteen districts or localities in Ontario, Quebec, and southeastern Manitoba, and in sixteen of these they recognized the Algoman granite. At present there are twenty-nine districts or localities, extending from Lake of the Woods to the Adirondacks, for which the sequence of the pre-Cambrian rocks has been published. In twenty of these, two granites widely separated in time appear, while in the other nine the Laurentian granite is absent and the later granite only is exposed. In none of these twenty-nine districts, nor at any other locality, do more than two groups of granite appear. If there were in reality a third granite period, it seems probable that somewhere in the extensive region under consideration the rocks of the three would appear together, and their failure to appear together creates a very strong presumption in favor of the view that there are two, and only two, pre-Cambrian periods of granitic development. Opposed to this hypothesis are the considerations which

[4] Jour. Geol., vol. xxiii, no. 8.

[5] Ontario Bureau of Mines, vol. xxii, no. 2.

have led Collins and Quirke to regard the Killarney granite as of Keweenawan age or later. What, then, are these considerations? They are:

1. The Killarney granite cuts rocks which are supposed to belong to the Cobalt series, and the latter has been correlated with the Animikie of Thunder Bay. Any intrusives which cut the rocks of Animikie age are presumably of Keweenawan age.

2. The hypothetical equivalent of the Killarney granite at Sudbury cuts the nickel-bearing norite, which has been very generally supposed to be Keweenawan in age.

3. The Killarney granite cuts certain quartz diabase dikes which are common in the Huronian rocks north of Lake Huron and which have been very generally supposed to be of Keweenawan age.

With regard to these considerations, some critical comments may be of service.

RELATION OF THE COBALT SERIES TO THE KILLARNEY GRANITE

While there is abundant evidence that the Killarney granite cuts the Bruce series, the statement that it is also intrusive in the Cobalt series perhaps requires more particular and detailed evidence to support it. At Killarney the granite, as mapped, comprises two distinct irruptives. The older one is a rather coarse-grained granite gneiss, which prevails to the west of the village, and the younger is a fine-grained red porphyry, in which a minute flow structure may be observed, on close inspection. In some specimens of the porphyry porphyritic quartz may be observed; in others no quartz can be detected, but it is probably a quartz-porphyry or micro-granite deficient in mica. The contact of the two rocks crosses the channel a few hundred feet to the east of the landing at the village, and on the south side of the channel one may step from the porphyry to the granite gneiss in one stride. A small dike of the porphyry cuts the gneiss at the contact. In the porphyry to the east of Killarney are several large inclusions of quartzite, which are represented on Collins's map, Number 155A, as an area of Mississagi quartzite. In the vicinity of these large inclusions of quartzite there are many smaller ones and some inclusions of the granite gneiss. Dikes of the porphyry cut the quartzite and show chilled margins, which resemble the quartzite adjoining and which have been mistaken for quartzite. The porphyry is clearly later than the granite gneiss and is the rock which displays most of the intrusive phenomena which have been ascribed to the granite at Killarney. The porphyry extends along the north shore of Lake Huron from the village of Killarney to the

granite gneiss at a point a short distance inside of Collins Inlet, at which the relations of the two rocks were not observed. The east-west extent of the porphyry is thus about 7 or 8 miles. To the east of the porphyry the granite gneiss is very extensive.

I examined these rocks to the east of Killarney with Quirke's paper on Killarney gneisses and migmatites[*] in my hand, and was surprised to find that the distinction between the porphyry and the granite gneiss was not recognized. This failure to perceive the existence of two irruptives led me to more closely scrutinize Quirke's evidence of "ultrametasomatism," and I was forced in the field to reject his conclusions. His statement as to the development of migmatites between Killarney and Collins Inlet is due probably to his failure to distinguish between the fine-grained porphyry and the altered quartzite, where the intrusion is complex. I had the great advantage of being guided over the bare rock surfaces by Collins, who pointed out to me the rocks which Quirke regards as migmatites; so that my conclusion is not a hasty one, but was formed in the presence of the evidence, while listening to a strong advocacy of Quirke's views. The rocks themselves told me a much more convincing story of other import. I may say, in order to discount any supposition of prejudice, that ever since my work on Lake of the Woods and Rainy Lake I have been a strong believer in migmatites, and I recognized them as an important class of rocks long before Sederholm's invention of the term. But the migmatites between Killarney and Collins Inlet are almost wholly of a mechanical sort, due to the inclusion of fragments of quartzite in the porphyry and to the ramification of apophyses of porphyry through the quartzite. There is, of course, a moderate amount of contact metamorphism, but this is less than might be expected at such contacts.

The quartzite which is included in the porphyry, and which Collins mapped as Mississagi, is identified by Quirke as "Lorrain" without discussion of the evidence for this correlation. This is a matter of some importance, since in one case the porphyry (called the Killarney granite) cuts the Cobalt series, while in the other it is known to cut only the Bruce series. I was unable, on the basis of field evidence, to determine whether these blocks of quartzite included in the porphyry are Mississagi or Lorrain, or possibly belong to some other formation. In Killarney Bay, rocks of the Bruce series (Lower Huronian) are mapped by both Collins and Quirke in close proximity to the granite, although

[*] Bull. Geol. Soc. Am., vol. 38, 1927, pp. 753-770.

the prevailing rock against the granite is the Lorrain quartzite. The juxtaposition of the Huronian rocks and the granite gneiss is, however, in part due to faulting, and I have found no clear statement of evidence that this granite gneiss is actually intrusive into the Lorrain. I do not deny that the granite gneiss is post-Cobalt, but the evidence that it is so is not very convincing.

It is worthy of note in this connection that Collins, in his paper on the geology of a portion of the Sudbury map area south of Wanpitei Lake,[7] states that the Killarney granite cuts the Mississagi quartzite; but there is no evidence, either in the text or on the map, that it cuts the rocks of the area mapped as Cobalt series.

In the region where the Killarney granite is supposed to present intrusive relations to the Cobalt rocks, namely, to the southeast of Lake Panache, it is not yet certain, on the basis of recorded evidence, that the rocks cut by the granite really belong to the Cobalt series. Quirke says:[8]

"Places where the granite is clearly intrusive into Huronian sediments lie about the northeastern part of Lake Panache and border Balsam Lake. However, along the main line of contact the relations are extremely complicated and variable. For part of the way, roughly from Killarney Bay to Kinley Lake, the contact appears to be that of an igneous intrusion, which followed a fault-plane, cutting obliquely across the strike of the anticlinal and synclinal structures of the Huronian formations."

The rocks at the northeast end of Lake Panache, into which the Killarney granite is intrusive, are the Mississagi quartzite of the Bruce series, and concerning this intrusive relation there is no question. The rocks about Balsam Lake and Bell Lake are mapped[9] by Collins as Cobalt series, although their apparent conformity with the Bruce series suggests that they may be rather the upper part of the latter, since there is normally a discordance between the Bruce series and the Cobalt series. On this mapping is based the post-Cobalt age of the Killarney granite. That there is some difficulty in distinguishing between the upper part of the Bruce series and the Cobalt series is evident from the fact that Collins,[10] on his special Map 124A of the territory south of Wanapitei Lake, shows a large area of Cobalt rocks traversed by the Wanapitei River, whereas this same area is referred to the Bruce series on his general Map 155A of 1922. Further, the fault to

[7] G. S. C. Summary Rpt. for 1913, pp. 189-195.
[8] Bull. Geol. Soc. Am., vol. 38, 1927, p. 756.
[9] G. S. C., Mem. 143, Map of Panache Lake.
[10] G. S. C., Summary Rpt., 1913, p. 189 et seq.

which Quirke refers appeared to me at the head of Killarney Bay to be postgranite. It would certainly be interesting to have some observational evidence of the fact that it is pregranite.

Geneva Lake is another place where "granitic intrusions were observed cutting the Bruce and Cobalt series."[11] But when I search for evidence of the post-Cobalt age of the granite, this is the best I can find:

"However, in the southeast corner of lot 3, Con. IV, Moncrief township, a syenite porphyry dike intrudes the Serpent formation which immediately underlies the Cobalt conglomerate."

This seems to be a rather feeble basis on which to establish the post-Cobalt age of the granite, the Serpent formation belonging to the Bruce series and separated from the Cobalt by a great unconformity.

Another locality where the Cobalt is mapped in contact with the Killarney granite is on the line of the Canadian National Railways, between Crerar and Chudleigh,[12] but I can not find anyone who has claimed that here the granite is intrusive in the Cobalt rocks.

These doubts as to the post-Cobalt age of the Killarney granite at the east end of the Huronian area appear to be resolved by relations revealed at the west end, near Lake Superior. In a recent paper[13] R. G. McConnell has described here two granites. The older of these cuts the basement schists and is overlain unconformably by the lower Huronian strata. It is evidently the Laurentian granite. McConnell calls it "Algoman," but the "Algoman" is by definition post-Huronian. The younger granite clearly cuts the whole of the Huronian, including the latest Cobalt rocks. It also cuts certain quartz-diabase dikes in the Huronian, but is older than the olivine diabase dikes of the region. It is lithologically similar to the Killarney and is correlated with it. This appears to settle the question of the relation of the Killarney granite to the Cobalt series and proves its post-Cobalt age.

AGE OF THE NICKEL-BEARING NORITE AT SUDBURY

There seems to be general agreement among those who have written about the geology of Sudbury that there are certain granites which cut the nickel-bearing norites. The norite is assumed by these same writers[14] to be of Keweenawan age; therefore the granite is Kewee-

[11] Quirke: G. S. C., Summary Rpt., 1920, part D, p. 16.

[12] G. S. C., Map 155A.

[13] Sault Ste. Marie area, District of Algoma. 35th Am. Rept. Ont. Dept. Mines, vol. xxxv, pt. ii, 1926.

[14] Barlow, Coleman, Miller and Knight, Collins, et al. In my correlation paper of 1916 I also correlated the norite with the Keweenawan.

nawan or post-Keweenawan in age. The logic is very fine, but how about the premises? What is the basis of our knowledge of the Keweenawan age of the great Sudbury laccolith? As far as I can discover from a search of the literature, there is no basis beyond pure assumption, and we have no knowledge of such equivalence in age.

The nickel-bearing norite and its associated micropegmatite are regarded by almost all writers on the geology of Sudbury as a laccolithic intrusion or sill, the roof of which is the Whitewater series and the floor of which is the surface on which that series once rested. In this they follow Coleman, who supposed that the so-called Trout Lake conglomerate, the basal formation of the Whitewater series, had suffered metamorphism as a result of the intrusion. But the Trout Lake conglomerate is not a conglomerate, but a volcanic agglomerate, and we have no recorded observations that justify the notion that this agglomerate has suffered contact metamorphism. In a brief examination of the Whitewater series, extending from Fairbank Lake across the Sudbury Basin to the Levack Mine, a section affording many excellent exposures, I found no evidence of contact metamorphism nor any dikes cutting the Whitewater rocks. Therefore it appears to me, both from the failure of the record to establish contact metamorphism and from my own field observations, that the Whitewater series may possibly be a late pre-Cambrian series resting on the eroded surface of the micropegmatite.

Now, Coleman has correlated the Whitewater series with the Animikie of Thunder Bay on the basis of lithological similarity and general stratigraphic position, but if the Whitewater series be Animikie in age and rest on the eroded surface of the micropegmatite, then the Sudbury laccolith must long antedate the Keweenawan. I am well aware of the suppositions involved in this conclusion, and I lay no more stress on it than I do on Coleman's dogmatic intuition that the Whitewater series antedates the laccolith. I am here concerned only with pointing out that, in the absence of observational evidence, one guess is as good as another.

Moreover, the dikes of fresh olivine diabase, which are very numerous throughout the entire region north of Lake Huron, extending from Lake Superior to Sudbury, are very probably the eastern manifestation of Keweenawan vulcanism. These dikes cut all the other rocks of the Sudbury district, as well as the ores in the norite. The latter had solidified and had been synclinally folded before the olivine diabase

dikes cut it, and there is thus some reason for regarding the nickel-bearing intrusion as pre-Keweenawan.

At the southwest end of the Sudbury basin, and probably elsewhere also, there is abundant evidence of acute deformation, both in the micropegmatite and in the rocks of the Whitewater series above it. The micropegmatite at many of the excellent exposures on Fairbank Lake is foliated and so rudely schistified. The plane of foliation dips southeast at a high angle—that is, it is about normal to the intrusive sheet as its attitude is represented in Coleman's sections.[15] Since it is normal to the intrusive sheet, the foliation can scarcely be interpreted as due to magmatic flow. The schistosity is a shear effect, due to deformative compressive stress in solid rock. The agglomerate and tuff above the micropegmatite on the north side of Fairbank Lake, called the Trout Lake conglomerate by Coleman, has the same foliation and schistosity as the underlying rock and the plane of foliation has the same attitude. The schistosity is, however, somewhat more pronounced. The Onwatin slate of the Sudbury Basin has had imposed on it a very pronounced cleavage at high angles with the stratification. These observations indicate very clearly that the micropegmatite and the Whitewater series of beds above it have been subjected together to the same deformative stress. The stress capable of inducing this schistosity and cleavage was of mountain-making magnitude and very probably was connected with the large-scale deformation that gave rise to the synclinal trough in which the Whitewater strata now lie. This trough is commonly regarded, in accordance with Coleman's ideas, as due to the collapse of the floor of the great sheet, sill, or laccolith on a still deeper reservoir at the time of the intrusion. There may be some truth in this supposition, but it is, nevertheless, an unsupported, even if plausible, supposition, and it is more probable, in view of the deformation observable in the micropegmatite and in the Whitewater rocks above referred to, that the syncline is essentially a deformational feature due to compressive stress.

Now the last mountain-making stress of which we have record in the Sudbury district is that which deformed the Cobalt series, and that deformation is similar in intensity to that which affected the norite-micropegmatite intrusive. The intrusive sheet can not be later than the stress which deformed it, and all the deformation had been completed before the region was cut by the olivine diabase dikes. On the very reasonable hypothesis, therefore, that the olivine diabase is the

[15] Jour. Geol., vol. xv, 1907, p. 763.

eastern manifestation of the Keeweenawan volcanic activity of Lake Superior, it appears that the Sudbury intrusion antedates an orogenic epoch which in turn antedates the Keweenawan. This makes it clear that no reliable conclusion can be drawn as to the Keweenawan or post-Keweenawan age of the Killarney granite from the fact that some of it cuts the nickel-bearing norite.

RELATION OF THE KILLARNEY GRANITE TO DIABASE DIKES

The argument, that because the Killarney granite cuts certain diabase dikes, therefore it is Keweenawan or post-Keweenawan in age, is without force. The dikes are, it is true, intrusive in the Huronian rocks, but it is probable that they are much older than the Keweenawan. There are many diabase (quartz-diabase) dikes and sills which cut the Cobalt rocks and which were in existence before the orogenic movement which folded the strata of that series. There are many more diabase dikes which cut the Bruce or older rocks on the eroded edges of which dikes the Cobalt series was deposited.[16] These dikes and sills can not be correlated with the Keweenawan, and the fact that the Killarney granite cuts them affords no basis for referring the latter to the Keweenawan or post-Keweenawan.

On the other hand, the numerous almost perfectly fresh olivine diabase dikes which are found in the region are the latest manifestation of igneous activity. These dikes came into existence after the orogenic movement which folded the Cobalt rocks and may with great probability be regarded as the eastern equivalent of the Keweenawan of Lake Superior; and, since these dikes cut the Killarney granite, we have, to say the least, a strong indication that the latter is not Keweenawan in age.

It is highly probable, moreover, that the Killarney granite of the Sault Sainte Marie area described by McConnell[17] was stripped of its cover and denuded to about its present condition before the outpouring of the Keweenawan lavas which lie in nearly flat attitudes on the near-by shores of Lake Superior. It may be, indeed, said that here we have a proof of the fact that the Killarney granite long antedates the Keweenawan.

From the foregoing discussion it appears that the Killarney granite is neither Keweenawan nor post-Keweenawan, and that the hypothesis

[16] W. G. Miller: Can. Min. Jour., April 20, 1923.

[17] Op. cit.

of two, and only two, pre-Cambrian granitic periods, which I advanced in 1916, has not been overthrown. I shall accordingly continue to use it as a valuable working hypothesis in the elucidation of problems of correlation, retaining for the Killarney granite the comprehensive designation Algoman.

In the region northwest of Lake Superior[15] I have shown that the Algoman granite is later than two great series of rocks, the Steep Rock, or Lower Huronian series, and the Seine, or Upper Huronian series, both of which are post-Laurentian. The Animikie rests on the peneplained surface of the Algoman granite. Now, since the Killarney granite is not Keweenawan or later, and since it cuts both lower (Bruce) and upper (Cobalt) Huronian, according to Collins, Quirke, and McConnell, there is at least a nominal parallelism between the sequence northwest of Lake Superior and that north of Lake Huron. I say nominal because there is still doubt as to the equivalence of the formations called Lower and Upper Huronian in the two regions. The Steep Rock series has been recognized without question as the equivalent of the Lower Huronian of the south side of Lake Superior, and no one has expressed any doubt as to the correlation of the latter with the Lower Huronian (Bruce) of Lake Huron. This unanimity of opinion as to the identity of the Lower Huronian throughout so extensive a territory is one of the most remarkable and most hopeful results of the bewildering discussions of pre-Cambrian geology.

When we come, however, to the Upper Huronian, the case is not so clear. On the hypothesis of two, and only two, periods of granitic development, the Laurentian and the Algoman, the Cobalt can not be the correlative of the Animikie, as a number of geologists, myself among them, have thought. In the light of McConnell's work, I see no escape from the conclusion that the Killarney granite is post-Cobalt or post-Huronian. This is the position in the time scale that I originally assigned to the Algoman. If we abandon this correlation of the Cobalt with the Animikie, then the parallelism of the sequence on the two sides of Lake Superior holds. The Cobalt series falls into the same general time interval as the Seine series, which rests unconformably on the Steep Rock series and is cut by the Algoman granite. The correlative of the Animikie in the region north of Lake Huron remains an open question.

[15] G. S. C., Mem. 40, 1913.

Age of the Sudbury Series[19]

In 1913 Coleman[20] segregated, under the name Sudbury series, a group of rocks in the Sudbury districts which had previously been regarded as part of the Huronian. He described the series as consisting of three formations, which he named as follows in descending sequence:

	Feet
Wanapitei quartzite	20,000
McKim graywacke	7,000
Copper Cliff arkose	2,000
	29,000

He considered the series younger than the Keewatin and older than the Laurentian; but, as he then considered the Killarney granite to be Laurentian, this pre-Laurentian age means merely that the series antedates the Killarney granite and is not, therefore, necessarily pre-Huronian. He considered the series as the equivalent of the Temiskaming series of Miller,[21] but preferred a new name for reasons that he did not make clear. On his Map Number 171, accompanying his paper on the nickel industry, the Sudbury series, though consisting of three formations, was mapped on a lithological basis in two colors, one representing quartzite and comprising both the Wanapitei quartzite and the Copper Cliff arkose, and the other representing the McKim graywacke. In none of the three papers referred to does he give any observational evidence for the stratigraphic sequence within his Sudbury series.

In 1925 Collins[22] accepted, with various expressions of doubt, the stratigraphic position assigned to the Sudbury series by Coleman, but reclaimed from it the Wanapitei quartzite, which he identified as the Mississagi quartzite, an important formation of the Lower Huronian. For the remaining formations, the McKim graywacke and the Copper

[19] This discussion of the age of the Sudbury series is a criticism of certain conclusions of both Coleman and Collins, but as a lifelong student of pre-Cambrian geology I yield to no one in my admiration and appreciation of the fine work of these eminent geologists, and I am particularly impressed with the great value and importance of the detailed studies which Collins has carried out in recent years in the Archean terranes of Canada.—A. C. L.

[20] The Sudbury series and its bearing on pre-Cambrian classification. Proc. Internat. Geol. Congress, 1913.

The nickel industry, with special reference to the Sudbury region, Ontario. Canada Dept. of Mines, Mines Branch, 1913.

The pre-Cambrian rocks north of Lake Huron, with special reference to the Sudbury series. Ontario Bureau of Mines, vol. xxiii, 1914, pp. 204-236.

[21] Notes on the cobalt area. Engineering and Mining Journal, vol. xcii, 1911, pp. 645-649.

[22] North shore of Lake Huron. G. S. C. Mem. 143, pp. 22-27.

Cliff arkose, he retained Coleman's term Sudbury series. Collins also accepted Coleman's unproved statement as to the stratigraphic sequence of the three constituent formations of the old Sudbury series and still regarded the new, greatly reduced Sudbury series as made up of pre-Huronian formations long antedating the Mississagi. On his general map [23] he represents this reduced Sudbury series as a very notable belt of pre-Huronian sediments extending from a point south of Wanapitei Lake to the vicinity of Algoma, a distance of 105 miles. The belt consists chiefly of thinly stratified graywacke with a steep to vertical dip. It is bounded on the south for the greater part of its extent by the Mississagi quartzite, and between the two formations there is exposed at many places a thick conglomerate. On the north side of the belt the Sudbury graywacke is in contact with the Keewatin as well as with the Mississagi, but the map does not show some thick bodies of quartzite that intervene between the graywacke and the Keewatin, presumably because they were considered part of the Sudbury series. They may well be, however, Mississagi quartzite. A granite, most probably the correlative of the Killarney granite, cuts the Sudbury series, notably to the west of Cutler.

It is difficult to reconcile the mapping of this belt of the Sudbury series with the notion that it is pre-Huronian—that is, pre-Mississagi. It does not appear anywhere else below the Mississagi quartzite and its disposition is that of an infolded syncline. During the past summer I visited the region between Lake Huron and Sudbury for the purpose of seeing the Killarney granite, and through the courtesy and hospitality of Collins I had some opportunity of studying the relations of the Sudbury series to the Mississagi quartzite. In the course of this field-work I came to the conclusion that the former rested on the latter, and that the belt referred to really is an infolded syncline of post-Mississagi rocks and not the basement on which the quartzite was deposited. This view I communicated to Collins in the field and we discussed the stratigraphic relations of the two series at various times. In these discussions I greatly admired my host's entire detachment from preconceptions and his perfectly impersonal, objective attitude. It was clearly a matter of indifference to him, as it was to me, which of the two series was the older, but we were both deeply concerned in getting at the facts in the matter.

In presenting some observations on the relations of the Sudbury and Mississagi series as mapped by Collins, I do not pretend to settle the

[23] G. S. C. Map 155A. Portions of the districts of Algoma, Sudbury, and Temiskaming, 1922.

question of what those relations are; but the observations and a brief discussion of their significance appear to be worth recording if only for the purpose of keeping the question open till such time as it may be more carefully studied and settled.

It is evident from even a cursory reading of Collins's Memoir 143 that he is in grave doubt as to the pre-Huronian age of the Sudbury series, and that he has no more real evidence than Coleman had on which to base that assignment. On page 27 he says he "is rather inclined to leave the Sudbury series in the pre-Huronian, where Coleman originally assigned it, because the evidence for moving it up into the Huronian is not yet convincing." On page 40 I find this statement:

"Its contact [speaking of the so called basal conglomerate of the Mississagi] with the Sudbury graywacke was observed 3 miles west of Massey and again just west of Espanola. . . . There is no evidence of unconformity in either case, etcetera."

On page 57 this appears:

". . . The steeply dipping Mississagi quartzite lies against graywacke of the Sudbury series without apparent discordance. In fact, there is so little indication of unconformity that some ground is afforded for doubting whether the Sudbury series really lies on the far side of so vast an interval as the Huronian-pre-Huronian unconformity."

While Collins freely expressed these doubts as to the pre-Huronian age of the Sudbury series, he nowhere seems to have doubted the stratigraphic position to which both he and Coleman assigned it, without evidence, below the Mississagi quartzite.

South of Worthington there is an east-west belt of Mississagi quartzite about 2 miles wide which presents almost continuous exposures for its entire width. The quartzites composing this belt have a prevailing southerly dip at high angles approaching the vertical, and they are very commonly cross-bedded, so that at no part of the section is there any doubt as to which is the top and which the bottom of the formation. In going from north to south across the belt the strata are encountered in ascending order and the southern side of the belt is the top of the section.

Paralleling this belt of Mississagi quartzite on its south side is a belt of evenly stratified argillitic "graywacke" mapped as Sudbury series by Collins.[24] Between the quartzite and the graywacke is a coarse pebble

[24] G. S. C. Map 155A.

and boulder conglomerate in which there are many fragments of quartzite. It seems clear that the Sudbury graywacke rests unconformably on the Mississagi quartzite with a basal conglomerate which locally runs into many hundreds of feet in thickness, but lenses out along the strike as is the habit of conglomerates.

At other localities—for example, the north side of Panache Lake—the cross-bedding of the Mississagi quartzite shows that the top and bottom of the formation are locally the reverse of what Collins supposed, and it is apparent that no use was made of this important feature as an aid to the elucidation of the stratigraphy.

The Ramsay Lake conglomerate at Sudbury is splendidly exposed on the north side of the lake, between the Mississagi quartzite on the south and the graywacke of the Sudbury series on the north, but the relations to the latter are obscured in part by the presence of a large intrusion of gabbro. Coleman stated that this conglomerate rests unconformably on both quartzite and graywacke, and so mapped it.[25] The conglomerate has a matrix resembling the graywacke and is thickly charged with boulders and angular spauls of quartzite identical with the immediately adjacent Mississagi quartzite. Coleman's statement that the conglomerate rests unconformably on the quartzite confirms the observation of Van Hise and Seaman,[26] who state that the conglomerate rests on the eroded edges of the quartzite and contains fragments of it. Collins[27] places this conglomerate between the Mississagi quartzite and the graywacke of his Sudbury series, and in this I agree with him; but he regards it as the basal conglomerate of the Mississagi quartzite resting on the Sudbury graywacke, and in this interpretation I differ with him. As it appears to me, the conglomerate is made up very largely of the erosional detritus of the quartzite and is the basal conglomerate of the graywacke, which therefore rests unconformably on the quartzite, but grades conformably into the graywacke, as Collins observed. In this connection Collins admits that, "on the whole, pebbles or boulders of the underlying Sudbury series are certainly not abundant and have not in any single instance been positively identified."[28]

About a mile to the southwest of Ramsay Lake the boundary between the Mississagi quartzite and the Sudbury graywacke is intersected by a north-south road, and here again the conglomerate lies between the

[25] The nickel industry. Dept. Mines, Mines Branch, no. 170, 1913.
[26] U. S. G. S. Bull. 360, 1909, p. 425.
[27] G. S. C. Mem. 143, 1925, p. 40.
[28] G. S. C. Mem. 143, 1925, p. 40.

two formations, discordantly on the quartzite and grading, as far as the matrix is concerned, into the graywacke. Again the conglomerate comprises many fragments of the quartzite.

Four and one-half miles to the northeast of Sudbury, on the road to Sudbury Junction, at a point about half a mile from the station, I found, on the southeast side of the belt of graywacke (Sudbury series), a thick conglomerate with numerous blocks of quartzite, and just beyond a few hundred feet is the Mississagi quartzite, extensively exposed. Here again the only reasonable interpretation that can be placed on the section is that the conglomerate rests uncomformably on the quartzite, and that it is the basal conglomerate of the formation called the Sudbury series.

On the northwest margin of the belt of graywacke which passes through the city of Sudbury, where the belt comes partly against granite and partly against quartzite,[29] there is also a conglomerate containing quartzite fragments. The quartzite which here bounds the graywacke is Coleman's Copper Cliff arkose, the lowermost formation of his Sudbury series. This also appears to me to be the basal conglomerate of the graywacke on the northwest side of a synclinal trough, though the structure of the latter has not been worked out. To the north of Worthington the same graywacke belt is similarly bounded on the north by a formation of white, gritty quartzite identical with the Mississagi quartzite and several thousand feet thick.

Since the Mississagi quartzite underlies unconformably the graywacke on the southeast margin of the latter in the vicinity of Sudbury, it is not easy to suggest any structure for the Sudbury series other than that of a closely appressed syncline. The only other interpretation is that the section is continuously ascending from southeast to northwest, and that the Copper Cliff arkose (the quartzite on the northwest side of the belt) is above the graywacke, the other limb of the great syncline being cut out by the intrusive rocks which flank it. But this is structurally improbable; indeed, it is impossible without a large fault, in view of the belt of Keewatin rocks which Collins represents[30] as bordering the Sudbury series on the northwest. The Copper Cliff arkose is said by Coleman to differ from the Mississagi quartzite in having a pinkish color and in resembling an igneous rock.

The evidence above set forth clearly indicates that the Sudbury series, in the restricted sense of Collins, rests unconformably on the Mississagi

[29] See Coleman's map of Copper Cliff Mine and vicinity. Ont. Bur. Mines, 14th Rept., part iii, 1905.

[30] G. S. C. Map 155A.

quartzite with a basal conglomerate. In harmony with this interpretation is the widespread unconformable superposition of the Mississagi on the Laurentian and Keewatin and the very limited contacts of the Sudbury series with those older rocks. Everywhere on the southeast side of the belt of Sudbury graywacke the latter is in contact with the Mississagi quartzite. On the northwest side, west of Worthington, the Mississagi quartzite everywhere intervenes between the graywacke and the pre-Huronian rocks, except for three miles between Algoma and Spragge, where a large fault brings them together. East of Worthington the graywacke is represented as in contact with the Keewatin; but here, also, extensive unmapped areas of Mississagi quartzite intervene between the graywacke and the Keewatin. The mapping alone clearly indicates that the Mississagi quartzite is the older formation.

On the geological map of Copper Cliff Mine and vicinity, Coleman [31] shows the graywacke, which he afterward named the McKim graywacke of his Sudbury series, with a marginal conglomerate resting against the granite which is mapped by Collins [32] as the Killarney granite. Coleman's mapping is probably quite accurate, since it is a detail of a small area, including Copper Cliff Mine, on a scale of 800 feet to the inch. If the granite is the younger of the two granites of the district and is with high probability the equivalent of the Killarney granite, what are its relations to the McKim graywacke (Sudbury series) at this contact? If the granite were intrusive in the conglomerate, Coleman would surely have mentioned the fact in his text; but he does not.

The relative positions of the McKim graywacke (Sudbury in the restricted sense) and the Mississagi quartzite being thus the reverse of what they are supposed to be by Coleman and Collins, it is necessary now to consider the stratigraphic classification of the upper of the two series. There is every reason to hold fast to the view of Collins, that the Bruce series is the lowermost division of the old Huronian. That being so, the claim that the Sudbury series is a pre-Huronian series disappears. Since it is post-Mississagi, shall we refer it to the Cobalt series? If not, shall we place it in the Bruce series unconformably above the Mississagi? Or shall we set it up as an independent third division of the old Huronian, between the Bruce and the Cobalt series?

As to the first of these three suggestions, there are some general considerations which favor it. Coleman,[33] referring to the Ramsay Lake conglomerate resting on the upturned edges of the quartzite, says: "Dr. Collins has traced this conglomerate northeast, with scarcely a break, to

[31] Ontario Bureau of Mines, 14th Rept., part iii.
[32] G. S. C. Map 155A.
[33] Ontario Bureau of Mines, Guide Book, 1913, p. 18.

the basal conglomerate at Cobalt." If this be so—that is, if the basal conglomerate of the McKim graywacke (Sudbury series) be the same as the basal conglomerate of the Cobalt series at Cobalt—there is no room for further argument. The McKim graywacke is Cobalt. Possibly, however, Collins might dissent from Coleman's appreciation of the results of this field-work.

A second general consideration favorable to the correlation of the Sudbury and Cobalt series is that when we view Collins's Map 155A, the area occupied by the Sudbury series is complementary to that occupied by the Cobalt series. Nowhere do the rocks of the two series come in contact. There is an extensive distribution of Cobalt rocks from Lake Temiskaming to Lake Wanapitei. On Collins's special map[34] this formation extends into Falconbridge township. In the same township, 2 miles to the west, the belt of Sudbury graywacke begins, and extends thence for 105 miles, to the exclusion of all Cobalt rocks. The belt ends at Algoma, and immediately the Cobalt formation appears on the map with an extensive distribution to the west of that point, to the entire exclusion of the Sudbury graywacke. This mutually exclusive mapping of the Cobalt and Sudbury series is not only peculiar; it is suggestive of the possibility that they are one and the same formation. As a piece of evidence, it would have little value by itself, but taken with other facts of like import it has weight.

The third general consideration suggestive of a Cobalt age for the Sudbury graywacke is the evidence which it presents of being at least partly of glacial origin. The rocks claimed by Coleman as tillite are peculiar to the Cobalt series and are not reported, so far as I am aware, from earlier formations, except that Collins says that the Bruce conglomerate resembles closely the supposedly glacial Gowganda conglomerate.

Now, the Ramsay Lake conglomerate has been referred to repeatedly by Coleman as a probable tillite; and, after a study of the extensive exposures north of the lake, I agree with him. Of course, when he expressed this view Coleman supposed that the conglomerate was later than the graywacke; but if, as Collins and I believe, the conglomerate lies between the Mississagi quartzite and the Sudbury graywacke, and, as I believe, is the basal conglomerate of the graywacke resting on the eroded surface of the Mississagi, then the glacial origin of the conglomerate would place it in harmony with the glacial features of the Cobalt elsewhere. Moreover, the Sudbury graywacke and its associated conglomerate present still more striking evidence of glacial deposition than is apparent at Ramsay Lake. In many exposures where the gray-

[34] G. S. C. Summary Rpt., 1913, p. 189 et seq.

wacke is very regularly and thinly bedded it presents the characteristics of an indurated varved clay. These may be well seen, for example, on the west side of Perch Lake, between Worthington and Victoria Mine. Here not only is the graywacke varved, but some limited portions of the varved strata are crumpled, with perfectly even bedding above and below the distorted layers. The phenomena are such as are usually ascribed to the shove of advancing ice, followed by deposition in the waters at the front of the ice after it has retreated.

In these thinly laminated shales, mapped as Sudbury graywacke, there are lenses of boulder conglomerate which can only be explained as due to the dropping of glacial drift by ice floating in still water. Of these conglomerates a good example may be seen half a mile northwest of Worthington. The matrix in which the boulders are imbedded is a fine fissile shale and the stratification of the latter bends around the boulders. Boulders up to 12 inches in diameter are isolated, and there appears to be no room for doubt as to their having been ice-borne.

If, then, the Sudbury series is in part or wholly of glacial origin, or, to put it more conservatively, if it has those same characteristics which have been interpreted as glacial in the Cobalt series, we have some basis for correlating the two series.

The evidence above set forth in favor of correlating the Sudbury series, in the restricted sense of Collins, with the Cobalt series would seem to exclude the two other possibilities of stratigraphic classification, namely, either placing the Sudbury in the upper part of the Bruce or between the Bruce and the Cobalt. It must be noted, however, that nowhere in the mapping of the Sudbury series does it rest on the upper formations of the Bruce series. In Victoria township it is in contact with the Espanola formation, but here the contact is probably the plane of the Murray fault. In both the Blind River and Panache Lake areas, one to the north and the other to the south of the Sudbury belt, the recognized Cobalt rests on the upper formations of the Bruce, and one would naturally expect that, if the Sudbury graywacke be of Cobalt age, somewhere on the margins of the 100-mile belt it also would be found resting on the Serpent or Espanola formations. This fact is adverse to the confident correlation of the Sudbury series with the Cobalt. Its importance is, however, minimized by the fact that there is a pronounced unconformity between the Bruce and the Cobalt, and that in the vast area to the north of Lake Wanapitei the whole of the Bruce series is absent below the Cobalt.

It should also be noted that the descriptions of the Copper Cliff arkose, the pink color, the porcelanous, felsite-like texture, the feebly marked stratification, recall those of the Serpent quartzite and suggest

that the arkose may be the Serpent. The McKim graywacke would, in this event, be the Espanola graywacke, the Ramsay Lake conglomerate would become the Bruce conglomerate, and the Sudbury series would be conveniently swallowed up by the Bruce. Thus, while much may be said in favor of referring the Sudbury series to the Cobalt, the evidence for its real position is far from conclusive.

If we recognize the Cobalt age of the Sudbury series, then the post-Cobalt age of the Killarney granite is the more firmly established by the intrusive relations of the Cutler (Killarney) granite to the Sudbury graywacke. Moreover, the Sudbury series can not then be the equivalent of the Temiskaming, as Miller, Coleman, and Collins have supposed, since the latter is clearly separated from the Cobalt by a great unconformity, but it might be the correlative of the Seine series.

Pre-Cambrian Peneplains

The two main subdivisions of the Huronian, the Bruce and the Cobalt series, are separated by an unconformity which represents a large erosion interval. Great thicknesses of the upper formations of the Bruce series were removed in that interval, so that the Gowganda formation rests directly in places on the Mississagi quartzite. In others not far distant the Gowganda rests directly on the Laurentian or Keewatin, the whole of the Mississagi having been apparently eroded away. Notwithstanding this large measure of erosion, the angular discordance between the two sets of strata is but slight, and parallelism of stratigraphic structures, where the two series come together, is, according to Collins, a common phenomenon. This means, of course, that the rocks of the Bruce series were subjected to very feeble, if any, deformation of an orogenic character prior to the deposition of the Cobalt beds. In the interval between the Bruce and the Cobalt the region was uplifted and profoundly degraded; but there was no acute folding of the formations.

The great thickness of the Bruce series, over 2 miles in maximum sections, and its prevailing shallow water or continental character indicate that it accumulated in a geosynclinal trough on the margin of a continental area which may be assumed to have extended northward for an indefinite distance. The area within which the Bruce rocks are now found is, of course, the minimum extent of the original geosynclinal area of Bruce sedimentation. In the region to the north of that area—for example, between Lake Wanapitei and Lake Temiskaming—extensive terranes of Cobalt rocks rest directly on the pre-Huronian surface, the Bruce being absent.

This direct superposition of the Cobalt rocks on the pre-Huronian basement may be explained in one of two ways: Either the erosion of the

Bruce formations was so thorough that they were completely removed over the region where they are now missing beneath the Cobalt, or the Bruce was never deposited in that region. On the basis of positive evidence, it is difficult to decide between these alternatives. There are, however, some general considerations which bear on the question. The probability, already mentioned, that the Bruce series accumulated in a geosynclinal trough at the southern margin of a continental area implies the existence of an extensive land surface to the north of the trough. That surface was one of low relief—a peneplain. As Collins [35] points out:

"The pre-Huronian (surface), judging from its even contact with the Bruce series, must have had a low, peneplain-like relief when Bruce sediments began to be deposited on it."

The true basal conglomerate of the Bruce series, rejecting the Ramsay Lake conglomerate, is, like most transgressive marine conglomerates, a thin deposit, not significant of torrential deltas; and conglomerate beds are practically absent through the Mississagi section. The sands that make up the great volume of the Mississagi quartzite are not very different from those accumulating on the margin of the great Canadian peneplain of today. The finer products of erosion were carried to the far side of the area of sand deposition by the tidal currents in shallow waters. These considerations indicate that the trough in which the Bruce sediments accumulated had its northern limit not far from the present northern edge of the Bruce formations, and that the latter never covered the peneplain to the north, on which the Cobalt formations now rest. This means that the Cobalt series rests on the same peneplain as that which by depression became the floor of the trough that holds the Bruce series—that is, the peneplain formed in the Epi-Laurentian interval.

It is, of course, possible, notwithstanding the considerations set forth above, that the very perfect peneplain on which the Cobalt formations rest in the region north of Lake Wanapitei was covered by a northern extension of the Bruce series and was exhumed by erosion in the interval between the Bruce and the Cobalt. This would, however, imply a very complete peneplanation in that interval, and evidence for this is lacking where the two series are in contact, nearer Lake Huron. Collins [36] states that the unconformity covers a stratigraphic range of not less than 1,700 feet, from the Mississagi to the upper Serpent, and suggests that

[35] G. S. C. Mem. 143, p. 60.
[36] G. S. C. Mem. 143, pp. 72, 73.

the surface on which the Cobalt was deposited was scarped, perhaps as the Paleozoic limestones on Manitoulin Island are at the present time.

On the whole, the absence of the Bruce beneath the Cobalt north of Lake Wanapitei may be better explained on the assumption that the region was a land surface in Bruce time, rather than by supposing thoroughgoing peneplanation in the Bruce-Cobalt interval.

The acute deformation of the region north of Lake Huron occurred in post-Cobalt time, and the mountain-making movement was limited to the area in which Bruce rocks now underlie the Cobalt—that is, it was limited to the area of the Bruce geosynclime and was an expression of the collapse of that heavily laden trough. After the folding of the strata the region was invaded by granitic magma (Killarney, Cutler, etcetera) and, in the long interval that followed, the mountain range that had taken the place of the geosynclinal trough was peneplained. This peneplain is a very striking feature of the region north of Lake Huron today. It is the surface which to the south passes below the Paleozoic, and to the north becomes nearly coincident with the earlier Epi-Laurentian peneplain, separated from the latter by a thin, residual veneer of flat-lying Cobalt strata. It truncates the highly inclined Cobalt and Bruce strata indifferently, and the Lacloche mountains,[37] composed of the homogeneous and resistant Lorrain quartzite, constitute a notable monadnock, rising a few hundred feet above the general level.

The more resistant portions of the outcropping rim of the Sudbury Basin, particularly on the north side, constitute another monadnock, for the peneplain extends across the whole of the Sudbury laccolith. By reason of uplift, shallow valleys have been sunk in the peneplain along belts of soft rock, and one of the broadest of these valleys is that known as Sudbury Basin. As a physiographic feature, the peneplain is even more strongly marked where it truncates the Killarney granite than where it crosses the diversely resistant Huronian formations. Here, then, to the north of Lake Huron, we have two periods in which geological time is recorded, not in terms of sedimentation, but in terms of erosion—two periods for which there are no bodies of strata that we may name, but during which there were evolved vast peneplains not less significant of the passage of geological time. The earlier of these periods is clearly post-Laurentian and pre-Huronian, and corresponds to the Epi-Laurentian interval of the Lake Superior region. The second period is not only post-Huronian, but is post-Algoman (that is, post-Killarney). It may correspond to the Eparchean interval of Lake Superior. But here we have to consider the possibility of post-Algon-

[37] G. S. C. Mem. 143, p. 9.

kian-pre-Cambrian time having been long enough to have effected a still later peneplanation of the region.

The Algonkian (Animikie and Keweenawan) formations of the south side of Lake Superior have been folded as acutely as the formations of the Sudbury Basin, and the two regions of similar deformation lie in the same general east-west belt, as Collins has pointed out. This suggests that the folding of the Whitewater series, the norite-micropegmatite sheet, and the Huronian strata may be referred to a post-Algonkian orogenic movement. That would, of course, make the second of the two peneplains above referred to post-Algonkian, and therefore long subsequent in its period of development to the Eparchean peneplain, which is so strikingly displayed on both sides of Lake Superior beneath the Animikie.

This suggestion of a possible post-Algonkian date for the folding of the Huronian strata is, however, negatived by facts which have already been cited:

In the Sault Sainte Marie area, McConnell [38] has shown that the Keweenawan lavas of the coast of Lake Superior rest on the eroded surface of the highly inclined Huronian beds. He says:

> "The Keweenawan lavas of Horseshoe Bay are in contact with the tilted greywackes and quartzites of the Lower Cobalt. The time interval separating the two formations was sufficiently prolonged to allow of the removal by erosion of the whole of the Upper and a portion of the Lower Cobalt."

It is clear, therefore, that the orogenic deformation of the Huronian formations north of Lake Huron long antedates the Algonkian.

This harmonizes with the fact that the Keweenawan olivine diabase dikes cut the Huronian after it had been folded. Moreover, this peneplain which truncates the folded Huronian strata is probably the same surface which passes beneath the Keweenawan lavas of the Lake Superior coast, although on this point further field observations are desirable. As has already been indicated, there seems to be little room for escape from the view that the Algoman granite, which cuts the folded Cobalt, was denuded to much its present condition near the coast of Lake Superior before the Keweenawan lavas were extruded. Our peneplain, therefore, can not be post-Algonkian in its essential futures. It seems fair, therefore, to correlate it with the Eparchean peneplain of Lake Superior. The fact that this peneplain is also the surface which passes below the Paleozoic does not detract from this conclusion. It merely means that the peneplain survived through the Algonkian into Cambrian time.

[38] Op. cit., p. 30.

Whether it was ever buried in the region north of Lake Huron, either generally or locally, by Algonkian deposits is not known.

Should it eventually be shown that the Whitewater series is not the roof of a laccolith, but rests on an erosional surface, then it may become necessary to recognize in the Sudbury Basin a local post-Algonkian deformation of the Eparchean peneplain, whereby a remnant of the Animikie formation has been downfolded and so preserved. If this really happened, then in time subsequent to that event the peneplain was reestablished over the fold, leaving the rim of the basin as a monadnock. This complication is, however, improbable, in view of Coleman's very positive, though unsupported, opinion that the Whitewater rocks were lifted from their original basement by the intrusion of the norite-micropegmatite.

Conclusion

The conclusions reached regarding the age of the Killarney granite and the age of the Sudbury series, together with the recognition of two historically important peneplains, one pre-Huronian, formed in the Epi-Laurentian interval, and the other formed subsequent to the deformation of the Huronian, are contributions to the body of data on which pre-Cambrian correlation must rest or to which it must at least conform. Using these data in the tentative correlation of the pre-Cambrian sequence north of Lake Huron with that northwest of Lake Superior, it may be said: In both regions we have the same two great earth movements which I have called the Laurentian and Algoman revolutions, each of which was followed by protracted periods of erosion, in which the land surfaces were peneplained. In both regions we have the Keewatin and Laurentian antecedent to the Epi-Laurentian interval of peneplanation. Between the latter and the Eparchean interval we have in both regions two sedimentary series variously named, but classed as Huronian, cut by the Algoman granite. The Animikie rests at Thunder Bay on the peneplain evolved in the Eparchean interval, and therefore is not Huronian in any sense. Its correlative north of Lake Huron is very uncertain and may be non-existent.

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MAGNITUDE OF THE SEDIMENTS BENEATH THE DEEP SEA [1]

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(Read before the Society December 31, 1927)

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INTRODUCTION

It seems to have been a common assumption that deposition beneath the waters of the deep sea—that is, at depths of two or more miles—has been so slow that the magnitude of the deposits is of little importance. It is the purpose of this inquiry to consider to what extent this assumption rests on facts and to what extent it can be sustained. The problem is difficult. The rates of deposition in the deep sea are unknown and no methods seem to have been devised by which they may be measured. It has usually been assumed that terrigenous sediments are not carried far from the shores of the lands on which they originate, and there has been built on this assumption the conclusion that great thicknesses of terrigenous sediments can not accumulate beneath deep waters far from land.

[1] Manuscript received by the Secretary of the Society June 4, 1928.

In following the problem into its various ramifications, there have been considered possible sources from which and by which terrigenous and other sediments might reach the deep sea; the quantities of material in suspension and solution in the deep-sea waters; possible rates of deposition; the extent and character of present deep-sea sediments; the length of geologic time; the portion of geologic time during which there may have been deep sea; the selective distribution of shallow-water and deep-sea sediments; the volume of sediments as indicated by the sodium in ocean waters, in the sediments, and in igneous rocks; and the magnitude of the deep-sea sediments throughout geologic time in comparison with those of the shallow water.

The entire consideration is highly speculative, but the results suggest that in magnitude the deep-sea sediments compare favorably with those of the shallow water and may exceed the latter. Another outcome is the suggestion that the quantity of lime in the earlier deep-sea sediments was small in comparison with the lime in the deep-sea sediments of the later geologic ages. The major factors in the problem seem to be the length of geologic time, the dimensions of the deep ocean basins, and the fact that no or few deep-sea sediments have ever been destroyed, whereas the shallow-water sediments have been repeatedly uplifted and partially destroyed, and with each uplift have contributed something of their constituents to the deep abysses of the sea.

Sources of Sediments reaching the deep Sea

The sediments which reach the floor of the deep sea are either organic or inorganic. Of the former there are the shells of radiolaria and foraminifera, the frustules of diatoms, the secretions of some of the algæ, and the shells of a few other organisms, most of the material being derived from the planktonic organisms, which to a greater or less extent now float in the surface waters and are deposited over all portions of the sea-bottom which are not so deep that the shells pass into solution before reaching bottom. For most of the calcareous forms this depth may be placed at approximately 16,000 feet. The siliceous shells may attain greater depths, but most of these seem to have gone into solution around 18,000 feet. These organic materials now constitute an important part of deep-sea deposits. It does not follow that they have always done so. Foraminifera have been in existence since the Ordovician, but they do not seem to have done much sediment-building before the Mississippian, and it is not known that they were important contributors to the deep-sea sediments of the Paleozoic and early Mesozoic. As lime contributors to the deep-sea sediments they seem to belong to the later geologic periods—the Cretaceous and, in particular, the Tertiary and

Recent. It is thus probable that their contributions to modern deep-sea sediments is entirely out of proportion to their contributions to the early Mesozoic and Paleozoic deep-sea sediments. The planktonic algæ should be excepted from this statement, as contributions from this source may have come before the beginning of the Paleozoic. Radiolaria are known from very early Paleozoic rocks; diatoms from rocks not earlier than middle Mesozoic; both seem not to have made important contributions to sediments until past the middle Mesozoic. Some lime and other substances probably are deposited in deep-sea sediments as consequences of reactions initiated by products of decay of organic matter or products of organic metabolism.

The inorganic constituents are clay, silica, iron oxide, small particles of resistant minerals, manganese oxides, phosphatic matter, minerals of igneous rocks whose direct origin is uncertain, matter which clearly is of volcanic origin, and rare particles believed to be of cosmic derivation. Lime and magnesian carbonate of inorganic precipitation may also be present.

It was Murray and Renard's [2] opinion that most of the clayey matter in deep sediments was of volcanic origin. However, when one considers the few volcanoes in the Atlantic and the long distances so many of those of the Pacific are from large areas of that ocean, there would seem to be no good reasons for believing that volcanic matter would be more apt to travel far from their sources than fine matter derived from the often not so distant lands. There is no doubt that some of the clayey matter is of volcanic origin, but there seem to be no good reasons for believing that such is the origin of the major portion. Wyville Thomson suggested that the red clay represented the insoluble constituents of organic matter whose soluble parts had gone into solution in sinking through the overlying waters.[3] It is probable that some of it has this origin.

Much material is dropped into the waters of the deep sea from the atmosphere, known to transport fine materials for long distances and in great volumes—volumes comparable to those that are water-borne. The many dust showers and the vast loess deposits are instructive in this respect. Free states [4] that Europe has received five and a half inches during the 3,000 years of record, equivalent to 266 tons per square mile per annum, and Udden [5] expressed the opinion, based on experimental data, that 850,000,000 tons of dust are carried 1,440 miles in the Missis-

[2] J. Murray and A. F. Renard: Deep-sea deposits. *Challenger* Repts., 1891, p. 190.
[3] W. Thomson: Proc. Roy. Soc., vol. 23, 1874, p. 47.
[4] E. E. Free: U. S. Bureau of Soils, Bull. 68, 1911, p. 99.
[5] J. A. Udden: Pop. Sci. Mon., vol. 49, 1896, pp. 655-664.

sippi Valley each year. This approximates the quantity of sediment the Mississippi River carries in suspension. Dust seems to be present in the surface portions of the atmosphere at all times. Aitkin [6] found the number of dust particles per cubic centimeter of air in various parts of England and on the continent to range to 150,000, recorded at Milan, Italy, on March 22, 1893, and averages of his data for 1890 and 1891 gave 1,562.9 and 1,475.8 dust particles per cubic centimeter respectively. Thoulet [7] has noted the occurrence in deep-sea deposits of rounded and angular grains of quartz, the quantity in some instances being large, and he concluded that the residue minerals of deep-sea sediments were of eolian transportation. During time of great aridity, and particularly before the development of much land vegetation, the quantity of sediments thus contributed to the deep sea must have been large.

It has frequently been stated that the fine sediments brought to salt water by streams are flocculated and shortly afterward precipitated. It is probable that this is correct for much, perhaps most, of the fine material brought to the sea; but there seem to be no good reasons for believing that there would be complete flocculation, or that the flocculated particles would be in such large masses as to be beyond the competency of the currents of the sea. One may reasonably expect large quantities to be conveyed far from land and attain wide distribution. It has been stated that muds of the Amazon are visible 300 miles from its mouth, and there must be a much wider radius of distribution over which the muds are not readily detected.

It is considered probable that stream-carried sediments reach the bottom of the deep sea. It is certain that the atmosphere deposits sediments over the entire ocean. Additional contributions probably are derived from erosion of the coasts and the shallow-water bottoms, particularly when the bottoms have been brought to the depth of wave base.[8] Other inorganic deep-sea sediments are derived from volcanic and meteoric contributions, from chemical reactions in the sea-water or water in the sediments, and the insoluble parts of organisms which in many instances can not be related to their organic sources.

The materials derived as described above are considered to be deposited in greater or less degree over the entire sea-bottom. The distribution is not considered to be equal, but it probably is more nearly so than is the case in any other environment in which sediments are deposited. The

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[6] J. Aitkin: Trans. Roy. Soc. Edinburgh, vol. 35, 1889, pp. 1-19; vol. 1895, pp. 17-49, 621.

[7] J. Thoulet: Origine éoliene des minéraux fins contenus dans les fonds marin. Comptes rendus, vol. 146, 1908, pp. 1346-1348.

[8] J. Barrell: Bull. Geol. Soc. Am., vol. 28, 1917, p. 784.

inorganic sediments thus are deposited with the various oozes in as great or greater quantities per time unit as they are over the red clay bottoms.

Matter in Sea-water in colloidal and gross Suspension which may be inorganically precipitated

Matter in solution in sea-water includes nearly everything, and much of it may be precipitated as inorganic sediment. The carbonates may thus be precipitated in large quantities, particularly as the warmer ocean waters are "substantially saturated with $CaCO_3$."[9] Murray and Renard[10] estimated the silica in solution as nearly constant and to average 1 in 250,000, equivalent to 17,000 tons in each cubic mile. A part of this may be precipitated as inorganic sediment. Manganese, phosphorus, and other substances are deposited in some forms on the deep-sea bottom, but it is not known to what extent these are of inorganic precipitation. Any matter thus precipitated by chemical reactions might be dissolved several times and precipitated before final or permanent deposition.[11]

Reade and Holland[12] state that "the sea may hold, carry about, and distribute such fine and microscopic sediments in quantities, if not commensurate, second only to the matter held in solution." . . . "The distribution of this finely divided matter is world-wide. The particles are so small that the lightest may be carried about by the least movement of the water. Thus, it is not improbable that the bottom depths of the ocean hold more matter in suspension than is found in the layers of water nearer the surface." Some of this sediment is termed "quartz dust," and the other part "consists mostly of clay and iron oxides, which are present in even the clearest of water, and some mica. Carbonate of lime is often found and, as our suspension experiments have conclusively shown, it is held up by the clay and is present in the form of particles and not in solution."

A sample of sea-water from the North Atlantic (latitude, 51° 21′ north; longitude, 31° west, about the middle of the North Atlantic) contained 1,601 tons of solid matter in suspension per cubic mile. A sample from the Mediterranean contained 2,031 tons and one from the North Sea 1,946 tons. In this inquiry the North Sea and Mediterranean samples are not considered, as the land is not far distant in each case.

[9] J. Johnston and E. D. Williamson: Jour. Geol., vol. 24, 1916, p. 735. See other references cited by present author in Treatise on sedimentation, 1925, p. 277.

[10] Murray and Renard: Op. cit., pp. 286-287.

[11] It is not considered worth while to discuss in detail the inorganic deposition of lime salts, as it does not seem that anything would be gained thereby.

[12] T. M. Reade and P. Holland: Sands and sediments. Proc. Liverpool Geol. Soc., vol. 10, 1905, pp. 155-156.

A sample from the Indian Ocean (latitude, 15° 46′ north; longitude, 58° 51′ east) contained 264 tons in each cubic mile.[13] The experiments of Murray and Irvine[14] suggest that the smaller quantity in the Indian Ocean may have been due to more rapid precipitation, their experiments showing that fine sediments are precipitated more rapidly in warm than in cold waters. Most of this solid matter in suspension probably is of colloidal dimensions. Murray and Irvine's experiments show that it remains almost indefinitely in suspension in normal sea-water.

It is fully appreciated that the limited data relating to the matter in suspension in sea-waters far from land does not have great value; but, as the quantity of 0.0052 gram per liter, or 1,601 tons per cubic mile, is small, it seems reasonable to assume this quantity as an approximation of the matter in suspension in the temperate waters of the sea. For convenience of calculation, the figure of 1,500 tons is taken. On the assumption that the waters of the deep sea cover 115,000,000 square miles and have an average depth of 2 miles, they would contain, on the basis of 1,500 tons per cubic mile, a total of 234,000,000,000 tons of sediment in suspension, or about twenty-one and one-half times the estimated quantity annually carried to the sea by streams.

Possible Rates of inorganic Deposition

Here nothing definite is known. The best that may be done is the erection of limits and within them to attempt the determination of a rate of deposition not beyond the abilities of the agents of supply. As a point of starting, it is assumed that of the estimated 1,500 tons per cubic mile of suspended matter in Atlantic waters, one-twelfth annually is deposited, the figure being taken as it is one-half the quantity per cubic mile in the waters of the Indian Ocean, as indicated by the sample therefrom. For water of the average depth of not less than 2 miles this would result in 250 tons annually being deposited over each square mile of the ocean floor. This is considerably more than is estimated annually to be brought to the sea by streams, thus indicating a rate of deposition which seems too large for the known agents of supply. An assumption of 100 tons over each square mile gives an annual deposit of 11,500,000,000 tons—a quantity equal to about two-thirds of the quantity estimated annually to be brought to the sea by streams. If the sediments have a specific gravity of 2 and pore space and water be disregarded, this gives a rate of deposition of one foot in 17,420 years. This figure seems still too large from the point of view of material

[13] Murray and Renard: Op. cit., p. 287.

[14] J. Murray and R. Irvine: On silica and the siliceous remains of organisms in modern seas. Proc. Roy. Soc. Edinburgh, vol. 18, 1891, p. 243.

brought to the sea, and in order not to place too great a burden on the contributing agents, one-fifth of the above figure is taken, or 20 tons are assumed to be deposited annually over each square mile. If this have a specific gravity of 2 and nothing be allowed for porosity and combined water, a rate of deposition of one foot in 87,100 years is given, equal to a thickness of 1/290 millimeter per annum, or about one-twentieth the thickness of a sheet of typewriter paper. This quantity is equal to about one-seventh of that estimated to be brought to the sea by streams, and it is thought that atmospheric dusting alone is competent to care for this, as quantities almost as large are known to have been deposited over large areas in a single dust shower and to have traveled over a thousand miles in addition.[15]

A slight check on the above estimate of deposition rate may be given by the rate of accumulation of globigerina ooze. "In the North Atlantic, telegraph operators think there are reasons for supposing that 1 inch of globigerina ooze accumulates in ten years." [16] If this rate of deposition be assumed as an average, some idea of the rate of deposition of the inorganic constituents of deep-sea deposits may be acquired from the quantity of inorganic matter in globigerina ooze. The composition of the globigerina ooze observed by the telegraph operators is not known to the present writer; it is assumed to have had the composition of average globigerina ooze. There is no failure to appreciate that this may not have been the case. Average globigerina ooze contains 33.89 per cent inorganic matter, which, at the rate of an inch of ooze in ten years, would require 600 years for the accumulation of one foot of inorganic sediment. This is one hundred and forty times more rapid deposition than arrived at above, suggesting that the rate of one foot in 87,100 years probably errs in being too small.

Another check may be found in a deep-sea deposit of Borneo. This is known as the Danau formation and covers 40,000 square kilometers. The rocks consist of radiolarian hornstones and red siliceous shales and are considered consolidated equivalents of red clays.[17] The thickness has not been determined, but Brouwer estimates it "as at least one hundred meters." [18] The suggested age is Jurassic, but what part of the system is represented does not seem to be known, but it is assumed that

[15] A. N. Winchell and E. R. Miller: The dustfall of March 9, 1918. Am. Jour. Sci., vol. 46, 1918, pp. 599-609; The dustfalls of March, 1918. Mon. Weather Review, vol. 46, 1918, pp. 502-506; The great dustfall of March 19, 1920. Am. Jour. Sci., vol. 3, 1922, pp. 349-362.

[16] J. Murray: Science of the sea, edited by G. H. Fowler, 1912, p. 209.

[17] G. A. F. Molengraaf; On oceanic deep-sea sediments of central Borneo. Koninklijke Akademie van Wetenschappen te Amsterdam. Sec. Sci., vol. 12, 1909-1910, pp. 141-147.

[18] H. A. Brouwer; Letter of January 10, 1928.

one-third of the Jurassic system is present. The ratio rests on no data and it may be much smaller or much greater. Schuchert's ratios show the Jurassic to slightly exceed 13 per cent of geologic time since the beginning of the Devonian; so that the Jurassic, according to recent estimates, represents about 40,000,000 years, during which, at the rate of deposition of one foot in 87,100 years, there would have been deposited about 460 feet. If the Danau formation represents a third of the Jurassic, the assumed rate of deposition is much too low.

The two checks afford a little confidence in the assumed rate of deposition and support the suggestion that it may err in being too low.

Area of the Floor of the deep Sea

The area of the floor of the present deep sea is known, but this inquiry needs not only the present area, but the area throughout geologic time. The sum of the areas covered by the red clay and the globigerina, radiolarian, diatom, and other oozes, and which have an average depth of two miles, equals 114,690,000 square miles or, in round numbers, 115,000,000 square miles.

Walther has expressed the opinion that there was no deep sea until the end of the Paleozoic as no Paleozoic faunal elements have been found in the present deep-sea faunas.[19] If Walther's opinion is correct, it follows that a probably great thickness of pre-Cambrian and Paleozoic shallow-water sediments is buried beneath the deep-sea sediments of later times. As these shallow-water sediments probably were deposited on subsiding areas, it is likely that they would have a far greater volume and thickness than would deep-sea sediments deposited during the same times. In this inquiry it is assumed that pre-Cambrian and Paleozoic deep seas existed, and that if the deep seas of all time are considered they would be equivalent to deep sea, with area like that of the present, extending as far back as the beginning of the Devonian. This assumption may not be correct, but to the extent that the deep seas of early geologic time were small, or did not exist, the volume of shallow-water sediments beneath the deep-sea sediments is large, and the assumption made postulates shallow-water sediments beneath those of the deep sea for all of pre-Devonian time. This is more than half of geologic time, suggesting a greater thickness of shallow-water sediments beneath the deep-sea sediments than the shallow-water sediments of the same time on the existing continental masses.

[19] J. Walther; Transactions by C. M. Le Vene: Origin and peopling of the deep sea. Am. Jour. Sci., vol. 31, 1911, pp. 55-64.

Length of geologic Time

Much uncertainty exists with respect to the length of geologic time; but, as each examination of this question for the past three decades generally has resulted in pushing the beginning of the Paleozoic farther into the past, it seems likely that present estimates do not give as large a figure as may be the case within a few decades.

Barrell [20] estimated that since the beginning of the Paleozoic 500,000,000 years have elapsed. Holmes and Lawson [21] give 567,000,000 years for the same part of the life of the earth. Using Schuchert's ratios [22] and the Holmes and Lawson figure gives, in round numbers, 359,000,000 years since the beginning of the Devonian, and with the Barrell estimate, 300,000,000 years.

Differential Selection of deep-sea and shallow-water Sediments

According to the estimate of von Tillo, sedimentary rocks veneer 75 per cent of the present areas of the continents, so that present sediments to a large extent are derived from sedimentary rocks. The distribution of the various geologic systems on the continents indicates that such has been the case at least since the beginning of the Paleozoic. Thus the sediments of the sea since the beginning of the Cambrian, so far as these are not of volcanic or cosmic derivation, to the extent probably of a major part, have been derived from destruction of sedimentary terranes. With each destruction these have yielded materials to the deeper bottoms in the form of quartz, iron oxide and hydroxide, aluminum hydrate, and hydrous silicates. The lime derived from the destruction of rocks in the early ages, so far as it was deposited, is thought to have had its deposition largely confined to the shallow waters of the continental margins, with the consequence that the sedimentary rocks of the continents contain a greater content of lime than is justified by the lime content of the original source rocks.[23] Thus, until the early Mesozoic, it is suggested that the deep-sea deposits consisted dominantly of insoluble and undecomposed matter. Since the abundant development of the lime-secreting planktonic protozoa in the Mesozoic, it is possible that lime deposition in the deep sea has assumed essentially equal quantitative importance to the aggregate of all other forms of deep-sea sedi-

[20] J. Barrell: Bull. Geol. Soc. Am., vol. 28, 1917, pp. 745-904.

[21] A. Holmes and R. W. Lawson: Calculation of the ages of the radioactive materials. Am. Jour. Sci., vol. 13, 1927, pp. 327-344.

[22] C. Schuchert: Textbook of Geology, 2d ed., 1924, p. 105.

[23] C. K. Leith and W. J. Mead: Metamorphic geology, 1915, pp. 67-78, 271-273. E. Steidtmann: The evolution of limestone and dolomite. Jour. Geol., vol. 19, 1911, pp. 392-408.

ments. It is suggested that this is opposite to what was the case in the earlier ages.

A fact of great importance in connection with deep-sea sediments is the virtual certainty that most, if not all, of those formed are still in existence.

Thickness of deep-sea Deposits

The generalization made on previous pages permits some inferences with respect to deep-sea deposits. The generalizations which have been made are as follows: Deep-sea areas since the beginning of the Devonian are estimated to have averaged, including all deep-sea areas since and before that time, 115,000,000 square miles. There is assumed a rate of deposition of one foot in 87,100 years, which probably errs in being under rather than over the correct rate. Recent estimates of time since the beginning of the Devonian range from 300,000,000 years (Barrell, Schuchert) to 359,000,000 years (Holmes and Lawson). On the basis of the minimum of the two figures of lime, there would have been deposited a little more than 3,400 feet of insoluble and undecomposed matter, and according to the maximum estimate a little more than 4,100 feet. The average is 3,750 feet. This is about seven-tenths of a mile of sediments, representing the insoluble and undecomposed matter derived from all sources spread over the 115,000,000 square miles of the deep-sea bottom. With nothing allowed for porosity and combined water, this indicates the burial beneath the deep ocean in excess of 80,000,000 cubic miles of sediments composed of insoluble and undecomposed matter. To this thickness and volume there must be added additional thicknesses and volumes to account for the siliceous and calcareous organic sediments which since at least the late Mesozoic have contributed largely to the deposits of some parts of the deep sea. This estimate does not include shallow-water sediments buried beneath the deep-sea sediments and deposited at times when the deep seas did not exist or were small.

Volume of the shallow-water Sediments

The writer estimates the average thickness of Paleozoic and later sediments beneath the 45,000,000 square miles underlain by sedimentary rocks to be one mile. There are vast areas where the thickness is less than one mile; on the other hand, there are many smaller areas where the thicknesses attain several miles. The sediments on the continental shelves are assumed to have an average thickness of three miles. This estimate perhaps errs in being too large, but there is little information on which to base an estimate. This estimate of thickness places 30,-

000,000 cubic miles of sediments on the continental shelves, or a total of 75,000,000 cubic miles on the continental masses. Additional sediments lie on the continental slopes below depths of 600 feet. The area of these slopes approximates 15,000,000 square miles, on which there must lie volumes of sediments which may have greater thicknesses than may be found on any part of the ocean bottom, and their volume may equal that of all the sediments on the continental masses. These in considerable part consist of muds and only to a slight extent have they been elevated above sealevel and most of those formed probably are still in existence.

Total Volume of deep-sea Sediments based on Salts in the Sea

On the basis of the sodium in the sediments and in the ocean, Clarke [24] has estimated the volume of the sediments as equivalent to a layer covering the entire earth to a thickness somewhat less than one-half mile. No consideration seems to have been given to the sediments beneath the sea, as it is stated that "the great masses of sediments on the bottom of the ocean are left out of account." It is possible that these sediments may contain almost as much sodium as exists in the waters of the ocean, and, if this sodium is taken into account, a much greater volume of sediments must be assumed to exist and a correspondingly greater thickness of igneous rocks must be assumed to have been destroyed. It should be noted that this greater thickness does not make it necessary to assume different figures relating to the constitution of the earth's crust, since the entire aggregate of deep-sea sediments may contain the elements in much the same ratios as they occur in igneous rocks.

Leith and Mead computed [25] that the decomposition of each 100 grams of the average igneous rock contributes in oxides 2.75 grams to the mineral matter dissolved in the sea, and to produce such dissolved matter there was involved the destruction of 72,000,000 cubic miles of igneous rocks, producing as a consequence 92,000,000 cubic miles of sediments, equivalent to a shell 0.46 mile thick over the entire earth. In this calculation the salts in the deep-sea sediments are not included and the conclusions do not affect the problem of the magnitude of the deep-sea sediments.

The assumption that the sodium in sea-waters and in the sediments was derived from the decomposition of igneous rocks raises the question as to when the release of most of the sodium was accomplished. As previously noted, three-fourths of the present land areas are veneered with sediments and the distribution of the Paleozoic and later systems

[24] F. W. Clarke: Data of geochemistry. Bull. 770, U. S. Geol. Surv., 1924, p. 31; Bull. 228, U. S. Geol. Surv., 1904, p. 20.

[25] C. K. Leith and W. J. Mead: Metamorphic geology, 1915, p. 73.

indicates an approximation to this ratio since the early Paleozoic, suggesting that the destruction of the igneous rocks to release the sodium occurred in major part in the pre-Cambrian periods—a suggestion previously made by Barrell [26] and others.

Comparison of the Volumes of the Deep-Sea and Shallow-Water Sediments

Deep-sea sediments consist of various calcareous oozes extending to depths of 15,000 to 16,000 feet, siliceous oozes to 17,000 or 18,000 feet, and to these and greater depths the red clay. It is assumed that, were the materials giving name to the oozes not present, red clay would cover the deep-sea bottom in approximately equal thickness and composition. On succeeding pages it is assumed that the insoluble constituents of the oozes represent the red clay with composition as the red clay. This assumption probably does not sufficiently depart from correctness to impair conclusions of a general nature. The data relating to distribution and composition of deep-sea sediments are taken from Murray and Renard.

Red clay covers 51,500,000 square miles of the deep-sea bottom. Murray and Renard give many analyses of red clay, but only those of clay derived from depths of 18,000 feet or more have been used in this calculation, as it seemed that clays derived from these depths would contain a minimum of organic derivation and also would have undergone the most solution in sinking from the surface. There are four analyses of clays from such depths. The recalculated average composition of the four analyses is as follows:

Miscellaneous	2.27 per cent
SiO_2	59.94
Al_2O_3	17.90
Fe_2O_3	14.64
$CaCO_3$	2.16 [27]
$MgCO_3$	3.00
Total	99.91

Sample	Latitude	Longitude	Depth, fathoms	$CaCO_3$, hypothetical combination
Bache 10162	34° 41′	73° 23′	2,990	28.27 per cent
4	32 29	73 28	3,038	21.94
6	32 33	73 14	3,014	16.56

The analyses are by F. G. Fairchild. The high lime content is to be noted. Attention will be called to this fact on later pages.

[26] J. Barrell: The evolution of the earth and its inhabitants, 1919, p. 56.

[27] Doctor T. Wayland Vaughan called the writer's attention to the following three analyses:

The miscellaneous consists of 34 per cent calcium sulphate, 30 per cent magnesium oxide, 33 per cent calcium oxide, and about 2 per cent calcium phosphate, about 50 per cent being calcium oxide when so calculated. The total content of magnesium oxide in the red clay is a little over 2.10 per cent, which is a little more than half the magnesia in the average igneous rock and about two-thirds the quantity of magnesia shown by Steiger's analysis of a composite of fifty-one samples of red clay.[28] It is fully appreciated that too much weight must not be given to the figures relating to minor constituents, as the analyses are not in sufficiently large number to yield a trustworthy average.

Subtracting the calcium carbonate from the average analysis, on the assumption that it is not one of the red clay constituents, and assuming that the average siliceous matter of organic origin in the red clay,[29] 2.39 per cent, is representative of the red clay of 18,000 feet or greater depth, and also subtracting this, leaves 95.36 per cent as insoluble and undecomposed residue which has been deposited on the deep-sea bottom in the various ways described on previous pages. It is possible that the calcium sulphate and phosphate and magnesium carbonate should not be included.

Recalculating the analysis to 100 per cent gives as follows:

Miscellaneous	2.37
SiO_2	60.36
Al_2O_3	18.78
Fe_2O_3	15.35
$MgCO_3$	3.14

Material of the composition shown by this analysis is assumed as the average composition of the seven-tenths mile of sediments which had settled through the two miles of ocean water covering the deep ocean bottom over an area of 115,000,000 square miles. While this was being deposited, there were also being laid down, over the red clay areas of depths of 18,000 feet or greater, 2.39 per cent of the original quantity in the form of silica of organic origin and 2.16 per cent of lime carbonate. Over red clay areas of less depth than 18,000 feet the quantities of these two materials would be much larger. The total organic silica and calcium carbonate is about one-twentieth of the quantity of insoluble and undecomposed material, equivalent to a thickness of about

[28] Data of geochemistry. Bull. 770, U. S. Geol. Surv., 1924, p. 518.

[29] This assumption is not likely to be correct, as the organic silica of these deepest red clays should be lower than the average, but the differentiation of organic silica can not be made with exactness and the general results are not impaired because of the assumption. The magnesium carbonate and calcium sulphate and phosphate may also owe their deposition to organic matter. This will afford some correction to the possible error of considering too much silica of organic origin.

one-thirtieth of a mile, making the total thickness over the red clay areas about twenty-two-thirtieths of a mile. This would be composed of 1,800,000 cubic miles of miscellaneous material, 48,000,000 cubic miles of silica, exclusive of the silica of organic origin, 15,000,000 cubic miles of alumina, 12,000,000 cubic miles of ferric oxide, and 2,500,000 cubic miles of magnesium carbonate. In addition, the red clays would have about 2,000,000 cubic miles of organic silica and 1,700,000 cubic miles of lime carbonate of organic or other precipitation.[30]

Radiolarian ooze covers 2,900,000 square miles of the ocean bottom. It is stated to contain an average of 4.01 per cent of lime carbonate of organic origin and 54.44 per cent of organic silica. The inorganic constituents are assumed to be of the nature of red clay. The ratio of the inorganic to organic constituents is as 1 to 1.38, suggesting that while seven-tenths of a mile of red clay constituents accumulated over the radiolarian ooze areas, there would have accumulated more than 0.96 mile of organic sediments, or a total thickness of 1.66 miles and 3,900,000 cubic miles of material. Of the organic constituents there would be 160,000 cubic miles of lime carbonate and 2,100,000 cubic miles of silica.

Diatom ooze covers 11,280,000 square miles of the ocean bed. Calcareous organisms form an average of 22.96 per cent and siliceous organisms an average of 41 per cent, a total of 63.96 per cent, leaving 36.04 per cent as material of red clay characteristics, with a thickness equal to seven-tenths of a mile. The ratio of the organic to the inorganic constituents is as 1.53 to 1, giving a total thickness to the diatom oozes of 1.77 miles and a total volume of 19,900,000 cubic miles. Of this 7,200,000 cubic miles is of red clay composition and there are 8,200,000 cubic miles of organic silica and 4,500,000 cubic miles of lime carbonate.

Globigerina ooze covers 49,520,000 square miles. Organic lime carbonate constitutes 64.47 per cent and organic silica 1.64 per cent, the ratio of the organic to the inorganic matter being as 1.89 to 1, giving for the organic matter a thickness equivalent to 1.32 miles and a total thick-

[30] It should be noted that the percentage of lime carbonate in the average red clay is much higher than the figure taken. This is also shown in the analyses derived from Doctor Vaughan. If the average per cent be taken, the quantity of lime carbonate will be much greater. The figures are given in the next lowest round number, parts of 100,000 and in some instances parts of a million being omitted. The percentages of the analyses are in terms of weight; they have been used as percentages of volume, as, except in the case of the ferric oxide, the specific gravities of the materials are not sufficiently different to impair the general conclusions. The calculations are open to criticism on the basis that the materials in the sediments are not in the forms shown in the analyses. Nothing has been allowed for porosity and combined water. It is not to be assumed that the figures represent exactness; but they are to be considered as representing orders of magnitude.

ness to the globigerina ooze of 2.02 miles. The total volume is 100,000,000 cubic miles, of which the insoluble and undecomposed matter constitutes 34,600,000 cubic miles. The organic silica is over a million cubic miles and the organic lime carbonate 64,000,000 cubic miles.

Adding these various figures, there are obtained 71,000,000 cubic miles of organic lime carbonate, 12,000,000 cubic miles of organic silica, and 80,000,000 cubic miles representing the red clay constituents, or a total of 163,000,000 cubic miles of material. These figures are based on the assumption that the various types of deep-sea sediments persist to the bottom of the deep-sea sedimentary column. It is not believed this is correct. It is possible that lime and other substances pass into solution after burial and return to the overlying waters,[21] and it is thought that all of the oozes grade into underlying sediments which are lower in organic constituents.

The sediments on the continents above sealevel are little more than half the calculated volume of the inorganic sediments in the deep-sea deposits and between 27 and 28 per cent of the total volume of the deep-sea sediments, so far as these may be calculated from the sediments of the present bottoms.

Problem of Lime in Shallow-Water and Deep-Sea Sediments

The great quantity of lime in the modern deep-sea sediments raises this substance to an unbalanced position, even when the figures for the red clay with respect to lime are placed extremely low. Had the figure of average content for lime been taken, or figures shown in the samples analyzed by Fairchild, the volume of lime would have been greater than is given in the above figures. It may be that much of the lime deposited does not so remain, but again passes into solution after burial. This question can not be answered.

It seems probable that the deposition of great volumes of lime in deep-sea sediments is a comparatively modern phenomenon. It is probable that there have been planktonic lime-secreting organisms from the beginning of, or even earlier than the Paleozoic, but the planktonic foraminifera which are responsible for much of the lime of the globigerina and other oozes do not seem to have become abundant until late in geologic time. Few planktonic forms occur abundantly before the middle Mesozoic. According to Schuchert's ratios, the time of effective lime precipitation by planktonic foraminifera represents about one-fifth of the time since the beginning of the Devonian. On this basis the lime carbonate deposits may be decreased to about 13,000,000 cubic miles and the

[21] This is suggested, but it is difficult to see how it may be done after the sediments are buried.

total volume of deep-sea sediments becomes 112,000,000 cubic miles. Moreover, as the planktonic lime-secreting forms did not become abundant until late Tertiary, the volume of lime carbonate may be further decreased. It thus may be that the aggregate of the deep-sea sediments may contain a deficiency of lime in spite of the fact that this substance forms such a large part of those now being deposited.

Attention has been called to the sedimentary rocks of the Mesozoic and earlier systems containing an excess of lime. This was explained on the basis that the lime-secreting organisms of those times were dominantly benthonic and confined to the shallow waters of the continental margins. The abundance of lime in the deep-sea deposits of the present suggests that a somewhat different condition from the one postulated for the earlier ages now obtains, and has obtained since the late Mesozoic, with the consequence that quantities of lime greater than in the earlier ages are now being deposited in the deep sea, the total quantity perhaps exceeding that deposited in the shallow water. This deposition in the deep sea lessens the quantity which may be deposited in the shallows and permanently removes this lime from the continental masses. If such deposition of lime in the deep sea continues into future ages, as the older sediments of the continents are destroyed, the excess of lime in the sedimentary rocks of the continents will become less because of losses to the deep sea, and it is possible that in the future the sedimentary rocks of the continents will contain only a small content of lime.[32]

Summary

On the basis of the deposition of 20 tons of insoluble and undecomposed matter per annum over each square mile of an ocean basin averaging since the beginning of the Devonian an area of 115,000,000 square miles and according to current estimates of geologic time, there has been deposited in the deep sea a volume of inorganic sediments approximating 80,000,000 cubic miles. During the same time there was deposited a large but unknown volume of sediments, consisting of lime carbonate, silica, and other substances, the precipitating agencies being in many instances planktonic organisms. Beneath these deep-sea sediments is buried an unknown, but possibly large, volume of shallow-water and continental slope sediments, whose total thickness at any place is a function of the length of time before there was deep sea at that place. It is suggested that the deep-sea sediments of the early ages were dominantly

[32] It seems that years ago Murray offered a speculation similar to the one here presented.

composed of insoluble and undecomposed materials, in contrast to the ages since the late Mesozoic, during which lime has been an important part of deep-sea sediments. This lime is permanently removed from the continental masses.

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RECLASSIFICATION OF THE ARTIODACTYL FAMILIES [1]

BY W. D. MATTHEW

(*Read before the Paleontological Society December 31, 1928*)

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The classification of the living Artiodactyla is a comparatively simple matter. They are divided into Bunodonta, including three families—pigs, peccaries, and hippopotami—and Selenodonta, or Ruminants, including all the rest. The modern selenodonts in turn are divided into Tylopoda, or camels; Tragulina, or chevrotains; and Pecora, the deer-antelope-cattle group. The characters of these groups are sharply marked in teeth and feet as well as in various features of the soft anatomy. The bunodonts all have in common round-cusped crushing teeth, powerful canine tusks of triangular form, four-toed feet with the metapodials more or less completely separate, simple stomach, and various other features of the soft anatomy. The selenodonts all have crescentic cusps on molars and premolars, the molars quadrate with four cusps, the premolars with two, the upper incisors reduced or missing, lower incisors and usually the canine small, procumbent, spatulate, the feet two-toed with the middle pair of metapodials united into a cannon bone, the stomach compound for ruminating, etcetera. These groups, as they stand today, are natural and clearly defined groups.

EXTINCT FAMILIES DIFFICULT TO PLACE UNDER CURRENT ARRANGEMENT

Many of the extinct Artiodactyla do not fit readily into these categories, and various attempts have been made to arrange or modify them

[1] Manuscript received by the Secretary of the Society February 25, 1929.

in some approximately natural relationship. The entelodonts, or so-called giant pigs of the early Tertiary, have bunodont molars and have been classed with the pigs, in spite of the fact that they have very little else in common. They have teeth much more like those of Carnivora, with large recurved canines of round-oval cross-section, premolars of wolflike type, and the feet are two-toed, with median pair of metapodials closely appressed, although not united into a cannon bone. Even the bunodont upper molars have merely a nominal resemblance to those of the modern bunodont artiodactyls; for while in all of the modern bunodonts the upper and lower molars are of equal width and very much alike, in the entelodonts the upper molars are much wider than the lower and differ in arrangement of the cusps. Throughout the characters of teeth, skull, and skeleton, the entelodonts show very distant relations to any of the modern families. Nevertheless, it has been customary to include them in the Bunodonta, and they were for a long time referred to the same family as the pigs.

The anthracotheres and anoplotheres of the early Tertiary are equally difficult to place. Their cheek teeth are somewhat intermediate in pattern, with cusps partly bunodont and partly selenodont, but with a fifth cusp, the paraconule, usually present on the upper molars. They have somewhat various specializations in the front teeth, intermediate between the entelodont and pig-peccary-hippo types, the anoplotheres, as their name indicates, with no tusks, but a uniformly graded series of front teeth. The anthracotheres and some, if not all, of the anoplotheres are four-toed, with short, piglike feet.

To accommodate these and related types of early Tertiary artiodactyls, the group Bunoselenodonta was proposed and has been very generally used, a number of imperfectly known types of doubtful position being placed in it.

Another group difficult to place is the American Oreodontidæ, which have selenodont teeth like the ruminants, but tusks resembling those of peccaries, except that the lower tusk is p_1 instead of c_1, and the incisors are a full double set of cropping type, unlike either ruminant or pig pattern. The feet are short, four-toed, resembling those of pigs, but still more like those of anthracotheres, to which they seem to be more or less related. These have been placed in the selenodont division, but they are very distantly related to the modern ruminants.

Another group of difficult position is the cænotheres, little rabbit-like animals with selenodont molars, a continuous graded series of front teeth like the anoplotheres, and short, four-toed feet. Their molars are

like most of the "bunoselenodont" group in having five cusps, but the extra cusp is the metaconule instead of the paraconule. Cænotheriidæ have likewise been referred to the selenodonts, as also to the bunoselenodonts. They certainly have no near relationship to the ruminants and do not have bunoselenodont teeth.

Still another early type of artiodactyl is *Xiphodon*, with selenodont molars, long, compressed premolars, continuous series of front teeth regularly graded, long, slender, two-toed feet, with the metapodials much appressed. In these and many minor details they agree with the earlier Camelidæ, but differ in five-cusped molars, the paraconule being distinct. The xiphodonts have been generally referred to the bunoselenodont group on account of the molar construction, in spite of their many points of affinity to the camels.

Stehlin's revised Classification based on Tooth Characters

In his monographic studies of Eocene Artiodactyla of Europe, Dr. H. G. Stehlin, of Basle, reconsidered and revised the relationship of these earlier groups of Artiodactyla, emphasizing a point to which Wortman had previously called attention, that in the upper molars of most Artiodactyla the postero-internal cusp is not the hypocone, as in most other bunodont mammals, but the metaconule of the original tritubercular molar. He showed, however, that in the entelodonts and dichobunids a true hypocone is present, making a six-cusped tooth, and that in the cænotheres the hypocone is present, but the paraconule absent, making a five-cusped tooth of distinct origin from the rest of the Artiodactyla, in which the hypocone is absent and paraconule present, making a five-cusped tooth, or absent, making a four-cusped tooth. This he made the fundamental basis for dividing the order into (1) Hypoconifera, including entelodonts and dichobunids; (2) Cænotheria, with the single family Cænotheriidæ, and (3) Euartiodactyla, including all the rest of the Artiodactyla. Stehlin's work was based almost exclusively on the study of the teeth and principally of the molar construction, and, while it is a great advance on the unnatural classification of previous writers, it exaggerates, as it seems to me, the importance of this single feature.

Need of using both Teeth and Feet for a natural Classification

Any natural classification of the extinct Artiodactyla, especially of the early Tertiary groups, is complicated by the fact that many of the genera are very imperfectly known. A large number, especially of the European genera, are known only from the teeth and jaws, or from the skull only,

the skeleton being unknown. Study of the skeletons of the better known and later Artiodactyla shows that the characters of the front teeth and of the feet are quite as distinctive and important in determining the relationships as are those of the molars. The resemblances and differences in the foot characters appear to be quite as fundamental as those in the teeth and should be fully considered in working out the natural affinities. It appears to be necessary to evaluate the relationships first of those genera which are known from complete material and then to associate the imperfectly known genera as best we can.

Palæodonta, or primitive Bunodonts

On this basis it appears that entelodonts and dichobunids are related in retaining with little modification what appears to be the primitive pattern of the bunodont artiodactyls, both as to molars, premolars, and anterior teeth. In most but not all of them a hypocone is developed and the cusps are rounded, upper molars wider than lower, premolars and canines and incisors of Carnivora type. *Entelodon* is completely didactyl, and in the dichobunids the lateral digits are much reduced in the three American Eocene genera in which the feet are known (*Diacodexis, Homacodon, Nanomeryx*). The skeleton does not appear to be known in any of the European genera that might be referred here. As this group does not conform to Stehlin's Hypoconifera, including certainly *Diacodexis* and provisionally several other genera with primitive bunodont teeth but no hypocone, it appears necessary to distinguish it under another name, as Palæodonta.

Hyodonta, or piglike Bunodonts

The three existing families of pigs, peccaries, and hippopotami are a natural group distinguished by bunodont or sub-bunodont molars, the upper and lower molars of similar width, by triangular canine tusks with procumbent incisors, the premolars submolariform or with angulate cusps, the feet short and tetradactyl, and with various other points of resemblance. These are not the Bunodonta of the older authors, which include all bunodont Artiodactyla, and I would suggest the name Hyodonta to cover them.

Ancodonta, or primitive tetradactyl Selenodonts

Then we have a large group, including the old bunoselenodonts with the Cænotheriidæ and Oreodontidæ, which have the four-toed short feet of the pig group, but partly or wholly selenodont molars, various speciali-

zations in the front teeth, and somewhat various constructions of the molars—some with five, others with four cusps. It is open to question whether these form a unit group, although the two extreme types, anthracotheres and oreodonts, show a good deal of community in skeleton characters and have been admitted by most authors as related. Provisionally they may be united under the group name of ANCODONTA.

TYLOPODA, OR CAMEL GROUP

The xiphodonts and camels I regard as unquestionably related, and between the earliest unmistakable camel *Poëbrotherium* of the Oligocene and the Eocene genus *Xiphodon* the resemblances are marked throughout skull and teeth, and especially the feet. These should be united under the name TYLOPODA. They are precociously didactyl, the fore and hind feet equally advanced, the premolars elongate, narrow, compressed, the front teeth in uniform graded series, etcetera.

PECORA, OR TRUE RUMINANT GROUP

The higher artiodactyl families may be grouped under the term PECORA, including the tragulids, cervids, giraffids, antilocaprids, and bovids. All are didactyl in the pes and all but the most primitive have a cannon bone of quite characteristic type; but the fore foot is less progressive and in many of the earlier types is functionally tetradactyl. All of them, from the earliest, have the navicular and cuboid united, and all except the Eocene *Archæomeryx* have lost the upper incisors. The upper canine is sometimes developed into a long, saberlike tusk, more generally lost; the lower canine is incisiform. These and various other characters distinguish the Pecora as an unquestionable natural group. The European Eocene Amphimerycidæ may be regarded as a protraguline group, already showing coössification of navicular cuboid.

SUMMARY

The foregoing arrangement of the artiodactyl families more nearly represents their natural relationship, I believe, than the older classifications. It leaves some of the imperfectly known extinct types provisionally associated or wholly doubtful. If the classification is really a natural one, it should be practicable, with more detailed study, to place these doubtful genera more securely.

The customary grouping of the families of Artiodactyla is unsatisfactory as regards the extinct forms of the older Tertiary. The following arrangement is suggested, which it is believed better represents the

natural affinities of the different families as shown by the characters of teeth and feet:

Dichobunidæ	PALÆODONTA	Primitive bunodont teeth.
Entelodontidæ		Subdidactyl or didactyl feet.
Dicotylidæ Suidæ Hippopotamidæ	HYODONTA	Specialized teeth, triangular canines. Tetradactyl feet.
Anthracotheriidæ (including Ancodontidæ) Anoplotheriidæ Cænotheriidæ Oreodontidæ	ANCODONTA	Bunoselenodont to selenodont teeth. Tetradactyl feet.
Xiphodontidæ	TYLOPODA	Precociously didactyl feet. Selenodont premolars compressed and subsequently reduced.
Camelidæ		
Amphimerycidæ Tragulidæ (including Hypertragulidæ) Cervidæ Giraffidæ (including Palæomerycidæ) Antilocapridæ Bovidæ	PECORA	Didactyl pes, with navicular and cuboid united. Manus tetradactyl, becoming didactyl. Cannon bone of characteristic type. Upper incisors and usually canine lost, lower canine incisiform.

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ALTERNATING OSCILLATORY MOVEMENT IN THE CHAZY AND LEVIS TROUGHS OF THE APPALACHIAN GEOSYNCLINE[1]

BY RUDOLF RUEDEMANN

(*Read before the Society December 28, 1928*)

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THE TWO TROUGHS

The mapping of the Capitol district, New York, consisting of the Schenectady, Cohoes, Albany, and Troy quadrangles, has clearly brought out certain stratigraphic and paleogeographic features of the Cambrian, Ozarkian, Canadian, and Ordovician formations of the district that had already been suggested by work on the Saratoga and Schuylerville quadrangles and which appear to be of more than local interest.

The district is a small sector of the western part of the great belt of Paleozoic unrest and mobility known as the Appalachian geosyncline. The stratigraphic work, which was made difficult by complicated Taconic and Appalachian folding and extensive overthrusts, has disclosed at least two completely different sets of formations, which range in age from Lower Cambrian to Middle Ordovician. These formations were deposited in two nearly parallel troughs or channels, which in the text on the Saratoga and Schuylerville quadrangles have been called the eastern and the western trough.

FORMATIONS OF THE EASTERN TROUGH

The eastern trough contains the Lower Cambrian formations, which probably include more than 1,400 feet of rock and which were divided

[1] Manuscript received by the Secretary of the Society January 16, 1928.

by me in 1914 into the Bomoseen grit, Mettawee slate, Eddy Hill grit, Schodack shale and limestone, Nassau beds, Diamond Rock quartzite, and Troy shale, the highest division.

On the Troy shale rests the Schaghticoke shale, containing *Dictyonema flabelliforme* and corresponding to the *Dictyonema* beds of Europe and Newfoundland, which were formerly placed at the top of the Cambrian, but are now in some countries, especially in Scandinavia and the Baltic countries, believed to be the basal beds of the Ordovician or of the Canadian, where that system is recognized.

The Schaghticoke shale is followed by the Deep Kill shale, 300 feet or more thick, a mass of graptolite shale that corresponds to the Beekmantown and probably also to the Lower Chazy. A fossiliferous limestone, called by me the Bald Mountain limestone, of Beekmantown age, is incorporated in this shale in the Schuylerville Quadrangle. Its fauna is quite distinct from that of the normal Beekmantown, being characterized by large forms of *Eccyliopterus,* known to Dr. Ulrich from Oklahoma. It carries, however, enough elements of the Fort Cassin division of the Beekmantown to be correlated with that formation.

On the Deep Kill shale rests the Normanskill shale, another typical graptolite shale, which, according to our estimates at Willard Mountain, is over 500 feet thick and possibly over 1,000. It is of upper Chazy age and may be in part of Black River age.

Probably on the Normanskill, though at most places inclosed in it by close folding, lies the Rysedorph Hill conglomerate, containing in its richly fossiliferous pebbles faunas that range in age from Lower Cambrian to Trenton.

Another narrow band of Trenton shaly limestone, found near the eastern edge of the area in only a few outcrops, has been called by me Tackawasick limestone. It appears as a band between Lower Cambrian and Upper Devonian rocks (Rensselaer grits) and has evidently been overthrust far out of place.

Next follows the thick mass of Snake Hill shales, over 2,000 feet thick, of Upper Trenton age.

Formations of the western Trough

Not a trace of any of these formations is found in the western trough, which contains a different series, although certain beds of the two series have been brought into contact by overthrusting from the east.

The beds in the western trough are the "normal" formations, which are named below in ascending order:

The Potsdam sandstone (with the Hoyt limestone); the Theresa formation and the Little Falls dolomite, which are not exposed in the Capitol

district because they are deeply buried under the top members of the series, but come to the surface directly north of the Capitol district, in the Saratoga Quadrangle. These beds have been fully described by Cushing and Ruedemann. They were formerly referred to the Upper Cambrian, but are now assigned to the Ozarkian system. The true Beekmantown is missing here, as well as the Chazy, but they extend into the trough farther north, in the Champlain basin. Then follow the Amsterdam limestone, of Black River age, and the basal Trenton, the Glen Falls limestone. The rest of the Trenton is represented by the Canajoharie shale and the Schenectady shale, both of which reach thicknesses of 1,000 to 2,000 feet. The Utica is not recognized in either set of formations. The Lorraine is represented in the western set by the Indian Ladder beds, which are homotaxial with the Southgate member of the Eden formation of the Ohio basin.

Diverse Sources of the Beds in the two Troughs

The fact that we have here two adjoining, entirely different sets of formations extending parallel to the Appalachian geosyncline is most satisfactorily explained by the assumption that they were formed in two different troughs or channels. The differences in the rocks as well as in the faunas seem to permit no other interpretation. The rocks of the eastern trough are prevailingly shales, the only exceptions being the Bald Mountain limestone, Rysedorph Hill conglomerate, and the Tackawasick limestone, none of them more than 100 feet thick and all of them of local, restricted distribution. The lower beds in the western channel consist entirely of sandstone, dolomite, and limestone. The composition of the beds of the eastern trough points to an eastern source of their material. The graptolite faunas also point unmistakably northeastward, the lower Saint Lawrence region and Newfoundland evidently having been their route of travel from the Atlantic into the basin. The Rysedorph Hill fauna includes a distinctly Atlantic element, of Trenton age, described by me in 1901, and since recognized in the Chambersburg limestone and other formations of the Appalachian geosyncline by Ulrich, Bassler, and Butts as far south as Alabama. The Snake Hill shale likewise contains elements of the Trenton of northeastern Canada, as I have pointed out in former publications.

On the other hand, the faunas of the western trough, at least the later part of them, point distinctly to western connections, most distinctly so in the three latest formations.

PRECAMBRIAN LAND BARRIER BETWEEN THE TROUGHS

The existence of these two sets of formations, with separate faunas, in the two areas indicate the presence of a land barrier that separated the areas through Cambrian, Ozarkian, Canadian, and Ordovician time. Its presence is not indicated in Silurian and Devonian time. This barrier evidently arose in Precambrian time, for it delimits the long belt of Lower Cambrian formations to the west. Low folds arose in Precambrian time in the Appalachian geosyncline, or in its Precambrian predecessor, Schuchert's "eastern proterozoic geosyncline," which in later Precambrian

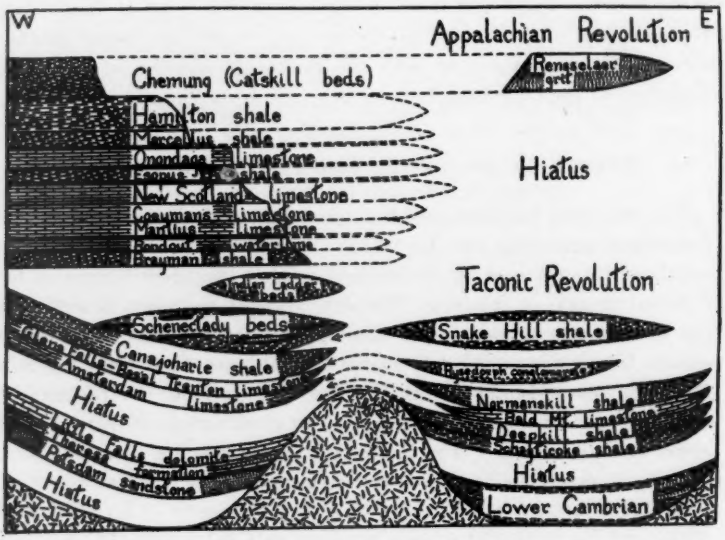

FIGURE 1.—*Formations and Diastrophism in the Capitol District of New York during Paleozoic Time*

The diagram shows the deposits of the two basins with the hiatuses due to non-deposition, the Precambrian barrier between the troughs, and the thrusting of the eastern trough against the western at the end of the Taconic revolution.

time extended from the northern Atlantic (or its ancestor, Poseidon) in an area beyond Newfoundland, southwestward to the present site of the Gulf of Mexico. To the east were the broad "borderlands" of the continent (Nova Scotis in the north, Appalachis in the south), which furnished the material for the thick formations in the eastern trough.

The existence of these two troughs and the separating barrier and of other features of the Appalachian geosyncline was first clearly recog-

nized by Ulrich and Schuchert,[2] who named the eastern trough the "Levis channel," after the Levis faunas, near Quebec, and the western trough the "Chazy basin," which is continued on the south by the Cumberland basin. The two channels are separated by the "Quebec barrier." The eastern trough is bounded on the east by the Green Mountains barrier; the western trough is bounded on the west by the Adirondack uplift in the north, and farther south by less distinct barriers, which perhaps were connected with the Helderberg barrier, delimiting the Cumberland basin.

Alternating Emergences and Submergences in the two Troughs

The work in the Capitol district has now brought out another fact that is of great significance, namely, that the formations in the two troughs are not only entirely distinct, but that the troughs were so independent of each other that when one was drained the other was submerged. The formations in one trough are not equivalent to those in the other. As figure 2 shows, there were at least four alternating submergences in the two troughs, the zigzag line in the figure indicating the alternation and the white blocks showing the formations laid down during the submergences.

Similar rhythmical Movements elsewhere

The rhythmic movement thus displayed may be the clue to some highly potent element in the mobility of the ever-changing crust of the earth. I have not found any records of similar oscillations of the land in adjoining basins, although certain oscillations were clearly recognized by Ulrich [3] in the southern part of the Appalachian geosyncline. The nearest approach to alternating submergences of this type is seen in the two blocks on the opposite sides of a fault near the lower Rhine, where movements occurred in Cretaceous and Tertiary time, as described to me recently by a visiting German geologist.[4]

A movement similar to that in the Capitol district seems to have been observed by T. O. Jones in the Llandovery district of Wales.[5] Dr. Jones found that in the folded regions of Wales described by him, "in addition to the differential subsidence and uplift along lines trending northeast

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[2] E. O. Ulrich and Charles Schuchert: Paleozoic seas and barriers in eastern North America. N. Y. State Mus. Bull. 52, 1902, pp. 633-663.

[3] E. O. Ulrich: Revision of the Paleozoic systems. Bull. Geol. Soc. Am., vol. 22, p. 512.

[4] W. C. Klein: Grundzüge der Geologie des Süd-Limburgischen Kohlengebietes. Ber. d. Niederrh. geol. Vereins, Jahrg. 1909, pp. 69-90.

[5] The geology of the Llandovery district. Quart. Jour. Geol. Soc., vol. 81, pt. 3, 1925, pp. 344-88; see, also, the author's abstract in Revue de Geologie, 1927, pp. 560-562.

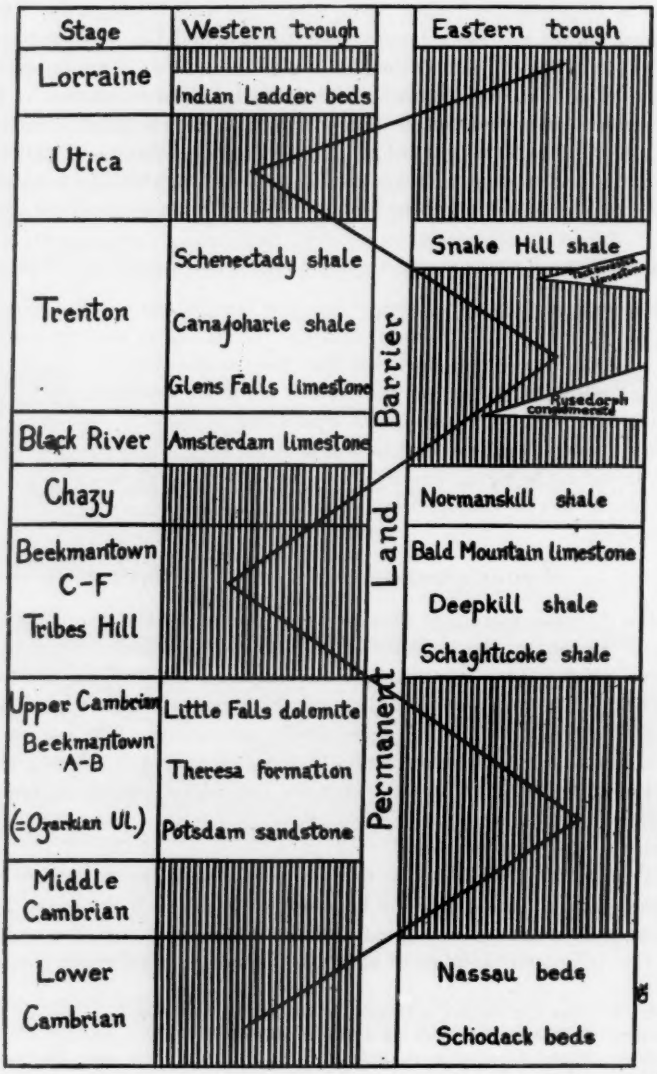

FIGURE 2.—*Formations of the Chazy Basin (western Trough) and Levis Channel (eastern Trough) in the Capitol District*

The zigzag line indicates the alternating submergence and emergence of the two troughs.

and southwest, there is evidence of repeated elevation and depression along nearly east and west axes" during Llandovery time, but not persisting into Wenlock time. He adds, that the discovery of "these intraformational movements is regarded as being among the most interesting results that the detailed examination of the district has produced."

In a general way, reversal of movement between the Appalachian geosyncline and the area to the west was observed also by Butts,[6] who states (page 378) that "the Appalachian geosyncline and a great area to the west were in a state of intermittent warping. At a given time one part was above water and another part below. At a later time the condition was reversed." There was, however, no such regularity of reversal as is found in the two adjoining troughs in New York.

Karpinsky describes rhythmic movement on a large scale in Russia, that country having been alternatingly submerged by movements from east to west and from north to south. European geologists suppose that this great movement was caused by subcrustal magmatic movements, but a similar great magmatic movement could not have caused the oscillations in the relatively small area here considered.

Theoretical Causes of the Movements

I have been unable to explain these movements as the result of isostatic adjustment, which is now so much favored by American geologists. It is true that geosynclines are zones of "isostatic sensitiveness," but such oscillations as are here considered would require much greater thicknesses of rock, and, in view of the known strength of the crust, would involve larger areas than those that were affected by these movements. The tendency to further sinking induced by the accumulation of sediments, if it is to be counteracted by the heating and the expansion of the lower beds to such an extent that the top is raised above sealevel, requires thicker masses of beds than are found here. A mile of rock would expand only about 9 feet[7] upward when heated by sinking, and in these reversals there was not more than half a mile of rock in one packet, the heating of which would not be sufficient to raise the surface above sealevel. It would be admissible, however, to regard isostatic adjustment as a means of increasing emergence.

I have tentatively adopted the theory advanced by Ulrich[8] in regard to the alternate tilting of interior areas of uplift, such as the two sides of

[6] Charles Butts: Variations in Appalachian stratigraphy. Jour. Wash. Acad. Sci., vol. 18, 1928, pp. 357-380.

[7] Letter from Dr. William Bowie of January 25, 1929.

[8] E. O. Ulrich: Revision of the Paleozoic systems. Bull. Geol. Soc. America, vol. 22, p. 430.

the Cincinnati dome. By applying to our two troughs this theory of the causes of differential tilting of interior domes or geanticlines, we should infer that their differential warping and subsidence may be due to the "oceanic spread" of Bailey Willis or to the pressure and thrusting exerted from the bottom of the Atlantic, which, when it has reached a violent stage, has led to orogenic revolution, but which, when pressing more steadily or less violently against the continent, would be fully competent to warp up the sediments of the eastern trough sufficiently to cause them to emerge from the sea. When this pressure was relaxed, perhaps by folding in an area farther east, the opposing force, the so-called "continental creep" of Chamberlain and Salisbury, which tends to spread the continent by gravity toward the deeper oceans, would act on the western trough, the force coming in this case from the interior of the continent. If this view is reasonable, we have before us a most excellent, almost diagrammatic, example of the effect of the interplay of these two slowly acting agents on the configuration of our continent.

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PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY

FOSSILS FROM THE PERMIAN TILLITE OF SÃO PAULO, BRAZIL, AND THEIR BEARING ON THE ORIGIN OF TILLITE[1]

BY RUDOLF RUEDEMANN

(Read before the Paleontological Society December 28, 1928)

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CHARACTER OF THE FOSSILS

Two decades ago Dr. John M. Clarke turned over to me for study a drawer of fossils that he had received from Dr. Orville A. Derby and which came from the Permian "tillite" of São Paulo, Brazil, determined as such, according to Derby's letter, by J. B. Woodworth. The material had been given to the New York State Museum and forms number 457 of its foreign collection, entered as "Fossils (Permian) from tillite in São Paulo, Brazil." Dr. Clarke added that the fossils looked to Derby like *Conularia*, but probably were not.

As I was then more interested in fossils from New York State, I gave the material only a very cursory examination and returned it without comment. The principal fossils were flattened triangular bodies, some as long as two inches, consisting of a white substance that strongly contrasted with the black shale in which they were imbedded and that under the lens was seen to be composed of fibers, mostly arranged transverse to the length of the bodies.

In 1927, on an excursion into the Ouachita Mountains with Mr. Hugh D. Miser and several other geologists, I found in the Wapanucka limestone, at Limestone Gap, Oklahoma, in a thin intercalated shale, fossils that at once reminded me of the Brazilian forms. They are tubular, flat bodies composed of closely packed sponge spicules, and further study

[1] Manuscript received by the Secretary of the Society February 20, 1929.

showed that they are coprolites. When I returned from Oklahoma I compared them with the Brazilian forms, which were also recognized as coprolites composed of fish bones and fish scales.

In the black shale from São Paulo, besides the coprolites, there were a number of shells of brachiopods belonging to the genera *Lingula* and *Orbiculoidea* and large patches of a lyssakine sponge. Besides the fish scales that are scattered through the coprolites, there are numerous detached scales and several patches of coherent scales. Mr. William M. Bryant, to whom I submitted the fish remains, writes me in a letter of July 14, 1928: "A cursory examination shows that the specimens contain scales and teeth of one or two species probably belonging to the family *Palæoniscidæ*." He adds: "At the same time there are two detached teeth which are crossopterygian. I suspect them to be teeth belonging to the fish which devoured the *Palæoniscidæ* and which broke off and were swallowed with them." This would make the coprolites those of crossopterygian fish. Mr. Bryant has since studied the material more closely and has given me the report appended to this paper.

This is a puzzling combination of fossils, indeed, to come from a tillite! There is no doubt that the fossils are those of marine forms and not such as could have been deposited in a fresh-water lake.

The State Museum contains also a collection of black fossiliferous shales found in a boring at Passinho, near Fernandes Pinheiro, in the State of Paraná, at a place described by Woodworth,[2] whose report includes a letter from Dr. E. P. Oliveira regarding this material. It appears from this letter that the fossiliferous shales there are 135 feet thick, and that they yielded a small *Lingula*, fish scales, and the remains of undetermined brachiopods and lamellibranchs. This occurrence is of special interest, for it shows that marine beds were deposited not only in São Paulo, but to the south and west, in Paraná, and are not merely local deposits.

The occurrence of this fossiliferous black shale in the enormously thick beds of Permian tillite of Brazil raises several questions.

Possibility that the Brazilian Beds of Tillite are glacial Drift

Fossiliferous beds are intercalated in Pleistocene glacial deposits in Iceland[3] and are regarded as evidence of repeated glaciation, the fauna containing, besides boreal forms, such as *Yoldia* (*Portlandia*) *arctica* and *Turritella erosa*, some forms that live in warmer seas, such as *Mytilus*

[2] J. B. Woodworth: Geological expedition to Brazil and Chile, 1912, pp. 47, 68.

[3] Helgi Pjetursson: Om Islands geologi. Meddelser Dansk Geol. Foren. No. 11, 1905, and Island, Handb. region. Geol. IV, 1.

edulis and *Purpurea lapillus*. In other words, the beds are interglacial.[4] Similar fossiliferous clay and sand containing the so-called Eem fauna are found in northern Germany in a narrow zone extending from the mouth of the Elbe River to Danzig and Elbing and thence up the Vistula River. The Cyprina clays of the Province of Westpreussen are correlated with the same formation. The interglacial beds at Stade, near the Elbe, contain oysters and other temperate marine forms and are bounded above and below by arctic clay marls containing *Yoldia* and other forms that indicate a change of climate. These German beds are referred to the first interglacial period and are regarded as indications of the existence of the Baltic Sea, which was overridden and filled by glacial ice.

One question, then, is, Do the Brazilian intercalated marine beds indicate an interglacial period in the Permian Glacial Epoch and a multiple glaciation?

Woodworth[5] sees in the marine fossils found by de Oliveira near Rio Negro, in São Paulo, evidence of an "at least temporary invasion of the district by the Permian sea." He found many granitic boulders in the beds of yellow tillite and intercalated dark shale, and he states that "the boulders range from two to three feet in diameter, with very few small pebbles, arguing for floating ice." The fossiliferous black shale in which de Oliveira found the marine fossils a few kilometers away is intercalated in two boulder beds of the tillite series. It is obvious that Woodworth considers the black shale an intercalation caused by a marginal marine invasion of the glaciated area.

The aspect of the faunule from the marine shale, with its large masses of sponges showing spicules several inches long, may suggest a warmer climate or an interglacial period, but on the whole it is unconvincing. It may be questioned whether a cold marine fauna existed at all in Permian time. The recent abyssal fauna is of Cretaceous origin, and no cold-water fauna that was able to descend to abyssal depth may have existed before Cretaceous time.

Permian glacial Beds of Argentina

Keidel[6] has shown the presence of beds of marine glacial origin of Permian age in Argentina. These beds, which are called the Tontal beds and which contain *Pleurotomaria* and *Spirifer* and glaciated pebbles, are found in an embayment that extends along the front of the

[4] Kayser: Lehrbuch der Geologie, vol. 4, 1924, p. 431.

[5] J. B. Woodworth: Idem, pp. 47, 68.

[6] Sobre la distribucion de los depositos glaciares del Pérmico conocidos en la Argentina [etc.]. Bol. Acad. Nac. Ciencias de Córdoba. Buenos Aires, 1922, p. 254.

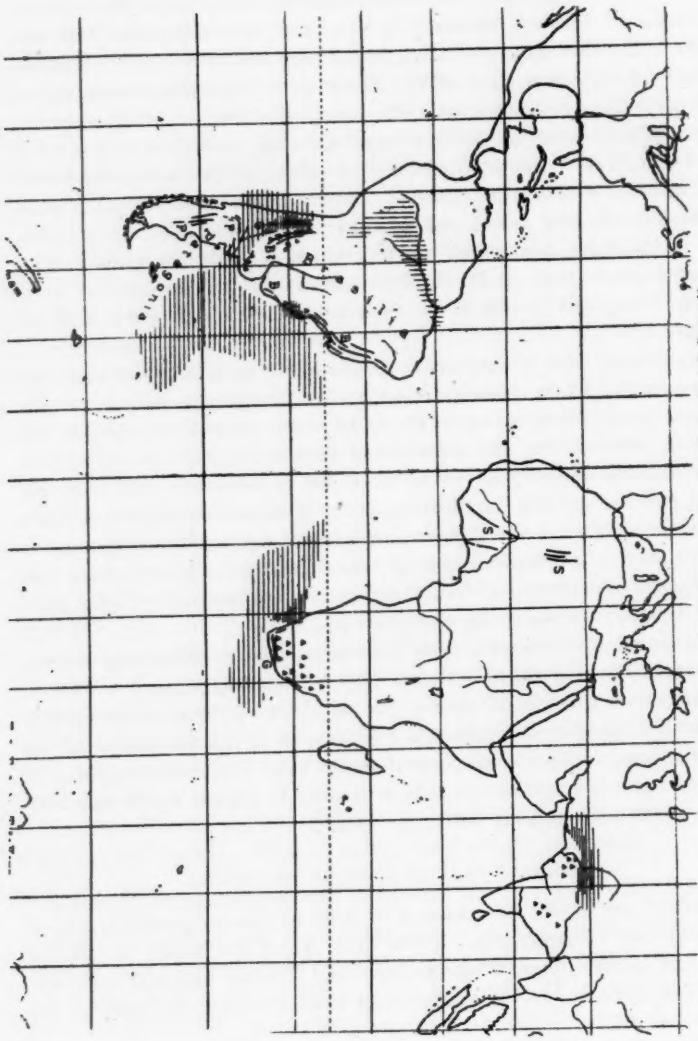

FIGURE 1.—*Distribution of the Permian glacial Deposits*

Part of a map by J. Keidel (1922). The ruling indicates the marine invasions; the triangles the distribution of Permian moraines in the lower Gondwana beds.

Andes and that lies west of an area of Permian tillite. The glaciomarine sediments indicate, according to Keidel, the beginning of an invasion of the sea, the eastern littoral beds of which became mixed with moraines. He correlates the Tontal beds with the Dwyka of South Africa and the Itararé series of Brazil, the name Itararé having been proposed for these beds by de Oliveira in 1916.

In South Africa, as in Brazil and Argentina, marine beds lie at the base of Permian tillite—a fact that precludes the assumption that they mark an interglacial period.

Marine fossiliferous beds have been found also in Permian tillite in Queensland, New South Wales, Tasmania, New Zealand, and India. In Queensland the marine beds, which have varved layers, reach a thickness of 4,800 feet. The *Glossopteris* flora is found both above and below them, and they therefore probably do not indicate a warmer interglacial period. The beds in both India and Australia contain *Eurydesma* and *Conularia*.

Another question is whether a large part of the Paleozoic tillites themselves may not be of submarine origin. After the drift theory proposed to explain the Pleistocene Glacial Period had been replaced, through the efforts of Agassiz and others, by the theory of continental ice, the possibility that glacial beds might have been formed from marine drift was entirely forgotten, but some geologists have recently pointed out the possibility that glacial beds, especially those of Paleozoic age, may be of marine origin. Keyes [7] asserts that the ancient tillites may be of berg origin; that they are not tills, but drifts, and that such boulder clays are today being formed in the North Atlantic as far south as New York and in the South Atlantic as far north as the Cape of Good Hope.

Kirk [8] states that "a considerable number of boulders brought up [in the cold waters of southeastern Alaska] were glaciated and were doubtless derived from present-day bergs," adding: "The present bottom sediments of the southeastern Alaskan fiords, if preserved as sedimentary rocks, would doubtless have all the characteristic features, in places at least, of tillites. In the sediments, however, would be found an abundant fauna."

Woodworth [9] reaches the conclusion that "it is the more reasonable to assume that the Permian ice deposits represent the existence of glaciers in the regions where the coarse accumulations occur, invoking as we may

[7] Charles Keyes: Glacial tills and iceberg drifts. The Pan-American Geologist, vol. 49, 1928, p. 369.

[8] Edwin Kirk: Fossil marine faunas as indicators of climatic conditions. Smithsonian Rept. for 1927, p. 301.

[9] J. B. Woodworth: Ibid., p. 90.

when the geologic evidence is permissible, a favorable geographical relief, such as now controls the distribution of glacial ice at one place or another on the earth's surface"; but he adds that "there are not wanting signs of ice action, probably floating ice, in the preceding Carboniferous epoch."

Several facts, however, distinguish the Permian tillite of Brazil from the Pleistocene beds and may indicate the submarine origin of a large part of the tillite. The most significant of these facts is the lack of glaciated rock floors beneath the tillite, although Woodworth [10] found pebbles that he considers fragments of broken-up floors. A further fact to be noted is the enormous thickness of the tillite, which in São Paulo, where the fossiliferous black shales are found, amounts to a minimum of 2,343 feet.[11] Finally, there is the presence of great masses of a peculiar yellow sandy "tillite" containing very few pebbles, which, in Woodworth's opinion, indicates floating ice. On the other hand, we must remember that not only the black shale containing the marine fossils, but the *Stereosternum* beds, which are much higher up, have been considered marine, though Woodworth holds that this interpretation of them has not been proved. In the middle of the section there are beds containing trunks of trees. These beds Woodworth [12] regards as sandstones formed on plains such as are now built up in front of glaciers or in similar situations permitting the growth of trees between times of aggradation by debris-laden streams. We must also remember that in the boring at Passinho ashy shale containing a rich *Glossopteris* flora was found directly above the marine beds.

I may add that the discovery, in Brazil and South Africa, of marine beds (with *Eurydesma* and *Conularia*) in the Permian tillite led Woodworth [13] to conclude that the glaciated lands of southern Brazil and of southwestern Africa stood in Permian time at or near sealevel, and that Schuchert's paleogeographic map of these regions in early Permian time [14] shows that the ocean reached close to the glaciated areas of South America, Africa, and Australia, making it possible that beds of ice drift may have been formed in the adjoining seas.

Permian glacial Beds of South Africa

In this connection the conditions found in the more extensively studied beds of South African Permian tillite may be illuminating.

[10] Idem, p. 76.
[11] Idem, p. 61.
[12] Idem, p. 62.
[13] Idem, p. 89.
[14] Pirsson and Schuchert's Text-book of Geology, part 2, p. 431.

The Dwyka conglomerate of South Africa, which is in places more than 300 feet thick, has been recognized as a tillite; indeed, the term tillite was first applied to that South African formation. In that region a polished and scratched rock floor is found at many places, and whole *roches moutonnées* landscapes are known, so that there can be no doubt of extensive ice action there. Nevertheless, the southwestern region has afforded alternations of peculiar sandy argillaceous beds, which are regarded as fluvio-glacial deposits formed at the margin of the ice, as well as calcareous shaly beds containing, besides the peculiar pelecypod *Eurydesma,* which is common also in the Permian of India and Australia, the remains of *Palæoniscus* and a *Conularia,* a truly marine fauna.[15]

The occurrence in South Africa of *Palæoniscus* and *Conularia* is suggestive, in view of the fact that the coprolites from Brazil were first compared with *Conularia.* It seems fair to conclude that the Brazilian and the South African shales represent similar conditions, if not equivalent beds.

The South African marine beds have been regarded as proof of an invasion of the African continent by the Permo-Carboniferous sea, but the inference of Wagner [16] appears to be simpler. He assumes that the deposits were formed outside of the continental ice-sheets by debris-covered ice floating in the sea.[17] The trend of opinion in South Africa is, therefore, in the same direction that we have followed, and if the sandy shaly beds that alternate with the fossiliferous beds are identical with the yellow sandy beds of Brazil, a large part of the glacial beds of Southwest Africa may have been formed by drift.

The characteristic elements of the faunules of the marine beds intercalated in the tillite—the *Palæoniscidæ* in America and Africa, the *Eurydesma* and *Conularia* in the other countries—indicate that the conditions in the sea around the glaciated area differed from those in the open ocean and suggest either a cooling or a slight freshening of the water surrounding the ice, or both.

I make these suggestions mainly in the hope of stimulating further research on the problem considered rather than for the purpose of establishing a new hypothesis.

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[15] Discovered by Lotz and Range. See H. Schröder: Jahrb. preuss. geol. Landesanst., 1908, I, 694. Also, P. Range: Beitr. zur Erforschung der deutschen Schutzgebiete, Heft 2, Geologie des deutschen Namalandes, p. 29. Berlin, 1912.

[16] Percy Wagner: Dwyka series. Trans. Geol. Soc. South Africa, vol. 18, p. 102. Johannesburg, 1916.

[17] Kayser: Lehrbuch, vol. 3, p. 401.

NOTE.—I had not had access to de Oliveira's report,[18] in which the Itararé beds and their fossils are described, until after I had written this paper. The following is a translation of his remarks on the beds and faunas:

In 1908 we discovered, near the city of Rio Negro, on the road to Itayópolis, in the town of Bella Vista, 6 kilometers south of the city, a bed of black shale, exposed for two meters, somewhat bituminous, containing argillo-calcareous nodules, intercalated in variegated shales containing big blocks of granite and other old rocks. The variegated shales present, in certain features, the characters of tillites.

In the shale we discovered a small *Lingula* exactly like that from Passinho, a small *Discina*, ganoid fishes, hairlike sponge spicules, and, in greater abundance, a problematic fossil, in regard to which we have vainly consulted various specialists. Thus it is definitely proved that the fossiliferous bed belongs to the Itararé series.

The problematic fossil mentioned is the coprolite.

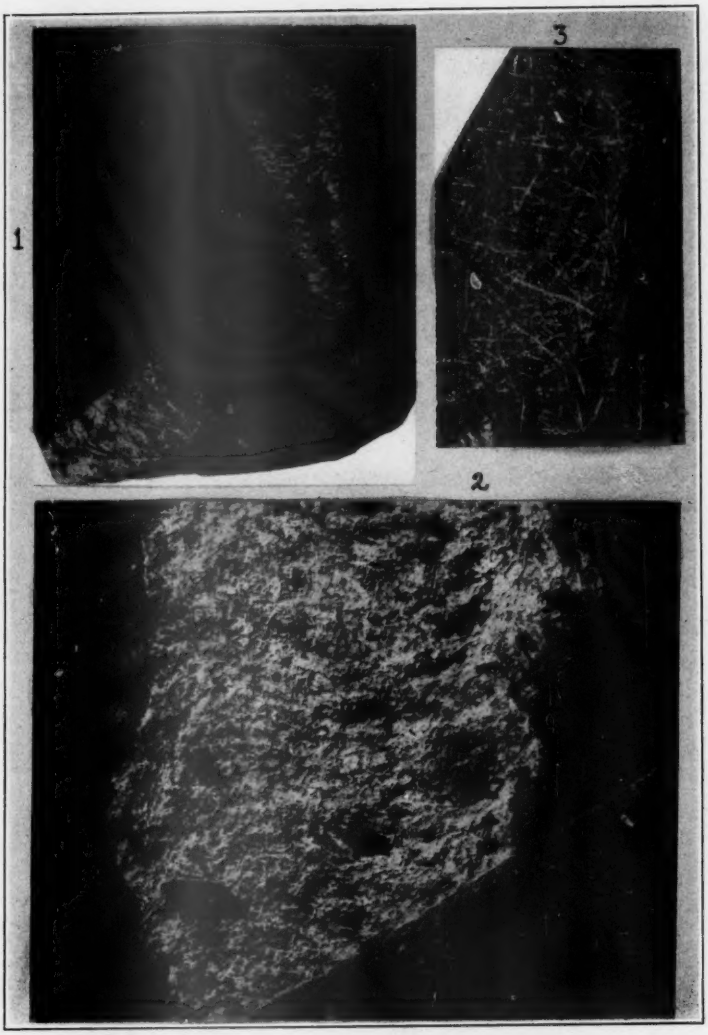
FOSSIL FISH REMAINS FROM THE PERMIAN TILLITE OF BRAZIL, BY WILLIAM L. BRYANT

I have examined with interest the small fragments of fossiliferous shale from the Permian tillite of Brazil sent to me by Dr. Rudolf Ruedemann. All of them contain fish remains—either detached scales or teeth. Several exhibit flattened coprolites, which in outline and in the arrangement of the undigested particles of food show that they have passed through intestines equipped with spiral valves. Entangled among the ejected food in these coprolites are a number of small fish scales; other scales, which are free, are sparingly scattered in the layers of shale.

Most of the scales can be referred almost certainly to the family *Palæoniscidæ*, supposed to be fresh-water or estuarine fishes. As to the genus one can not be so definite. These scales are of the peg-and-socket variety and are deeply sculptured. Three caudal scales in natural association and still interlocked show the deeply overlapping surface and ornament suggestive of *Acrolepis*. Others that have more prominent pegs and sockets may belong in or near the genus *Elonichthys*. One well-preserved scale, apparently cycloid, must be referred to another family.

Among the detached teeth there is one which has a base that is deeply grooved by the infolding of its outer walls and that can be confidently identified as a crossopterygian tooth, but, as it was the only specimen of

[18] Geologia do Estado do Paraná: Bol. Ministerio Agricultura Industria e Commercio, Ann. 5, No. 1, 1916, IV, pp. 67-143, especially p. 101.



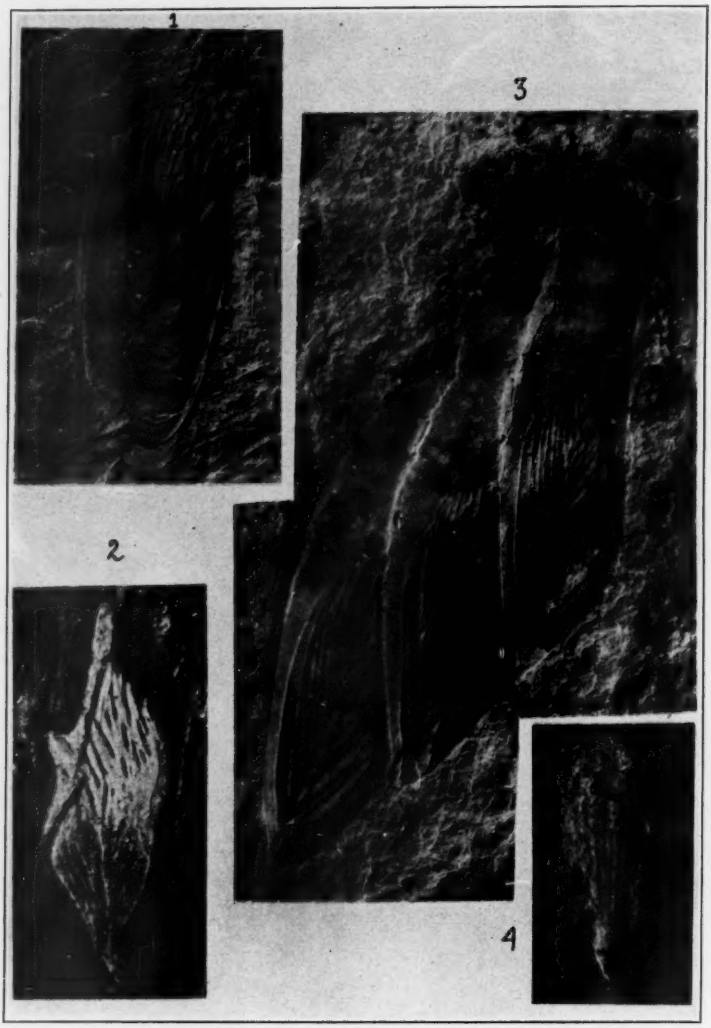
PERMIAN TILLITE FROM SAO PAULO, BRAZIL

Originals in New York State Museum

FIGURE 1.—Part of a slab, with fish coprolites. Natural size.

FIGURE 2.—Part of a coprolite enlarged to show fish scales and transverse fibrous structure. × 5.

FIGURE 3.—Patch of sponge tissue, with hexactins. × 5.



PERMIAN TILLITE FROM SAO PAULO, BRAZIL

Originals in New York State Museum

FIGURES 1, 2.—Two well-preserved scales, one surrounded by large sponge spicules.

FIGURE 3.—Three caudal scales in natural association, suggestive of Acrolepis. × 6.5.

FIGURE 4.—Detached tooth, regarded as crossopterygian. × 5.

its kind, I did not section it. It may have belonged to the predatory fish that devoured the *Palæoniscidæ*.

All these remains are probably those of undescribed species, but better and more material must be furnished to enable their certain identification.

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ROCKY MOUNTAIN FRONT IN MONTANA[1]

BY ARTHUR BEVAN

(*Read before the Society December 29, 1927*)

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[1] Manuscript received by the Secretary of the Society, July 23, 1928.

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Introduction

Scope of paper

This paper is an outline and summary of the salient features of the geology of the Rocky Mountain front ranges in Montana. It is based on the results of field studies by the writer, supplemented by data obtained from the literature cited.

Most of the features considered have been observed by the writer. A few areas have been examined in detail, but the exigencies of reconnaissance mapping prevented detailed work in much of the region; hence certain details of the stratigraphy, including the thickness of most of the formations, have been taken from published descriptions. The chief results of these studies have been to obtain a general knowledge of the geology of the region and to outline some of its major problems for detailed investigation. The opinions expressed should be considered tentative, for much detailed field-work must be done before many of the problems can be solved or positive conclusions can be stated.

Field-work and acknowledgments

Parts of the summers of 1916, 1917, and 1919 were spent in the Beartooth Mountains, where a reconnaissance areal survey was made and certain physiographic problems were studied in detail. During reconnaissance mapping of the Montana plains by the Montana Bureau of Mines in the summer of 1920 the writer was assigned to the western half of the plains. This assignment afforded some opportunity for preliminary studies along the entire Rocky Mountain front. The summer of 1921 and a month in 1922 were spent for the Bureau in reconnaissance mapping of much of the Big Belt Mountains and part of the east slope of the Continental Divide, to the northwest. Brief visits were made in the summer of 1926 to a few areas in and south of Glacier National Park.

The writer is glad to acknowledge his indebtedness to the Montana Bureau of Mines for the opportunity of studying the Big Belt Range and the mountain front to the northwest. He is especially under obligation to Dr. C. H. Clapp, former Director of the Bureau, for assistance in many ways. The field-work of 1920 was done jointly with Mr. G. S. Lambert. Mr. Royle C. Rowe was field assistant in 1921.

Elements of the Mountain Front

The Rocky Mountain front in Montana is not a continuous range, but a composite of several orographic units. Its general trend is almost northwest, but in its central part a broad elongate salient extends toward the plains, constituting a marked interruption of its somewhat linear

Figure 1.—*Rocky Mountain front Ranges in Montana*

character. Outlying ranges also affect to some extent the alignment of the front.

From south to north the front ranges are the Beartooth Mountains, Bridger Range, Little Belt Mountains, Big Snowy Range, Lewis and

Clark Range[2] and Lewis Range (figure 1). The frontal zone continues uninterrupted into northern Wyoming in the Beartooth Mountains and into Alberta in the Lewis Range. Across Bighorn Basin, east of the Beartooth Range, are the Pryor and Bighorn Mountains, which form the actual front ranges from southern Montana far into Wyoming, but they are not discussed in this paper. The Bridger Range is flanked on the east by the Crazy Mountains, which partly occupy a pronounced reentrant in the main frontal zone north of the Beartooth Range. Because of its volcanic character, this mass is not here considered an essential part of the main front ranges, but rather an outlying group whose history has been somewhat different from that of the major elements of the ranges. The Castle Mountains form a smaller outlying group, mainly of igneous origin, northwest of the Crazy Mountains. The embayments in the mountain front between the Little Belt Mountains and the Bridger Range, on the southwest, and the Lewis and Clark Range, on the northwest, are in part occupied by the extremities of the Big Belt Range, which, strictly speaking, is not an integral part of the frontal zone, but enters it, as indicated. It may be said that, if the eastern salient of the Little Belt Mountains be disregarded, the Big Belt Range stands in direct alignment with the other front ranges (figure 1). Northwest of Missouri River the mountain front continues as an almost unbroken lineament into Canada. In this part of Montana much of the area east of the Continental Divide belongs in the frontal zone, which obviously thus includes more than the actual mountain front.

In Glacier National Park the Livingston Range (Clarke Range of southern Alberta) is so closely related to the Lewis Range as to warrant its inclusion in this zone. To the south the outermost of a series of subparallel ridges in the Lewis and Clark Range constitutes the actual mountain front, but all members of the series are considered parts of the frontal zone. Northwest of Missouri River the frontal zone is thus somewhat more complex than southeast of the river.

The Little Belt Mountains interrupt the general northwesterly trend of the front. The northern part has a northwest-southeast axial trend, but this changes to an east-west trend farther south (figure 1). The axis continues eastward through the Big Snowy Mountains and into a

[2] No name has been applied to the entire front range between the southern end of Glacier National Park and Missouri River. It is in part a southward continuation of the Lewis Range, but differs markedly from it in structure, stratigraphy, and topography. Hence it seems advisable in this paper to call it the Lewis and Clark Range, after the National Forest which occupies much of it, although this name is somewhat infelicitous, because there is a Clarke Range west of the Lewis Range, in southern Alberta.

zone of less marked deformation that extends across central Montana. Hence the Little Belt-Big Snowy group forms a very prominent salient in the Rocky Mountain front.

This broad salient is bordered on the north by the Judith and Moccasin Mountains, ranges formed largely by igneous intrusions.

TOPOGRAPHY

As the general topography of this region is rather well known and as a description of its elements at this time would be premature, only those features that are especially impressive are here considered. The topography of the adjoining plains and of some parts of the mountain front has been described recently by Alden.[3]

FIGURE 2.—*Plainsward Front of Middle Part of Beartooth Range*

One of the most impressive features of the Rocky Mountain front in Montana is its abrupt rise from the Great Plains throughout much of its length. This feature is especially pronounced along the Beartooth Range (figure 2) and the front range from Dearborn Canyon northwest into Alberta. The plainsward crest of the Beartooth Range rises sharply 3,500 to more than 4,500 feet above the plains, reaching altitudes of 9,500 to 11,000 feet. Along Glacier National Park and south of it for

[3] W. C. Alden: Physiographic development of the northern Great Plains. Bull. Geol. Soc. Am., vol. 35, 1924, pp. 385-424.

about 100 miles the mountain front is sharply marked and generally exceptionally steep (figures 3 and 4). The elevation is commonly about 4,500 to 5,500 feet in the larger valleys and about 8,000 to 9,000 feet at the plainsward crest. The sharp, almost linear, demarcation of the front in these districts is caused by movements and differential erosion along huge faults.

Between Yellowstone and Missouri rivers the front is generally less abrupt and the relief is not so great. The east slope of the Bridger Range, however, rises rather steeply from about 6,000 feet at the base to

FIGURE 3.—*Rocky Mountain Front south of Sun Canyon, Saypo Quadrangle*

The ridge is west-dipping Mississippian limestone, with Mesozoic strata in front.

more than 9,000 feet at the crest. The Little Belt and Big Snowy Mountains stand about 3,000 feet above the adjoining plains.

Another striking feature of the topography in the frontal zone is the accordance of summit levels in some of the ranges. Extensive flattish subsummit plateaus, which represent a dissected peneplain, are seen in the Beartooth Range[4] (figure 2). The Little Belt Mountains contain many flattish summit tracts, which are commonly interpreted as remnants of a peneplain. The folded strata of the Big Belt Range are

[4] Arthur Bevan: Rocky Mountain peneplains northeast of Yellowstone Park. Jour. Geol., vol. 33, 1925, pp. 563-587.

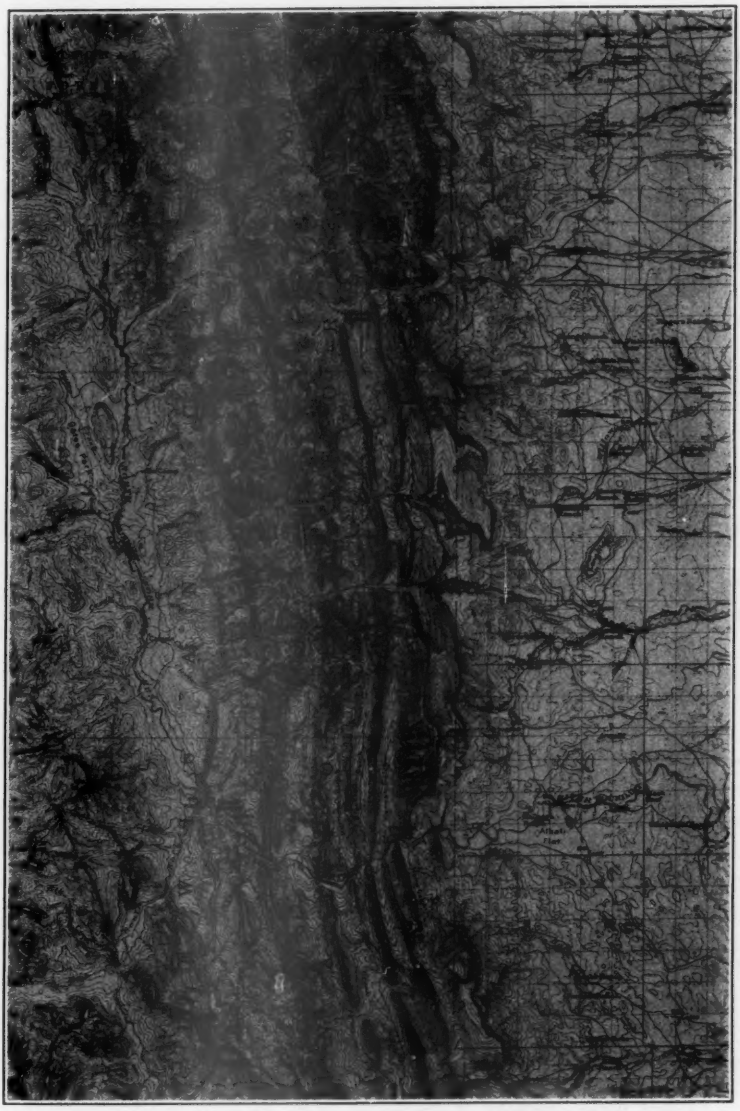

FIGURE 4.—*Topographic Map of Saypo Quadrangle*

Scale, 1/125,000; contour interval, 100 feet.

beveled at high levels in a few places. Rough accordance of crests is rather characteristic of the ridges southeast of Glacier National Park, especially in the Saypo Quadrangle (figure 4). East Flattop Mountain, along the east flank of the Lewis Range, represents an old erosion level.[5]

The drainage of the east slope of the Continental Divide is not of uniform type. It has certain peculiar characteristics, which are probably inherited, in part at least, from earlier cycles in the different ranges. The Beartooth Range, for example, is drained in all directions by tributaries of Yellowstone River. Trellised drainage is excellently developed among the parallel ridges of the Saypo Quadrangle. Interrupted cycles are well shown in some of the front ranges and on the adjoining plains.[6]

The northern and southern front ranges in Montana were severely glaciated during at least two or three stages. This glaciation left a marked impress on the erosional topography of these ranges and formed conspicuous deposits on the plains. The writer has studied carefully only the Beartooth Range. Alden and others have made detailed studies of the glaciation along the mountain front in northern Montana. The Little Belt and Big Belt Mountains were locally glaciated. The high altitude of the Crazy Mountains permitted extensive local glaciation.

Stratigraphy

General statement

A rather complete section of the stratigraphy of the northern Rocky Mountains is shown in the Montana front ranges and the adjacent foothills. The formations range in age from Archean to Recent, all post-Proterozoic systems being represented except possibly the Silurian and most of the Tertiary. The prism of sediments that was deposited in this part of the Cordilleran geosyncline, or Laramide trough, is enormously thick. The total maxima of the formations in this general zone give a thickness of at least 37,000 feet.

Precambrian

Archean.—Gneisses and schists of several types, presumably of Archeozoic age, form the main body of the Beartooth Range[7] and crop out extensively in the Bridger Range[8] and the Little Belt Mountains.[9] In

[5] Bailey Willis: Stratigraphy and structure, Lewis and Livingston ranges, Montana. Bull. Geol. Soc. Am., vol. 13, 1902, pp. 311, 337.

[6] W. C. Alden: Op. cit.

[7] Authur Bevan: Summary of the geology of the Beartooth Mountains, Montana. Jour. Geol., vol. 31, 1923, p. 443.

[8] J. P. Iddings and W. H. Weed: U. S. Geol. Survey Geol. Atlas, Livingston Folio, No. 1, 1894.

[9] W. H. Weed: Little Belt Mountains Folio, No. 56, 1899.

the two ranges last named they are overlain in places by Proterozoic sediments, but they underlie Cambrian strata throughout the Beartooth Mountains. Archean rocks are unknown elsewhere in the region.

Proterozoic.—The Proterozoic rocks consist of the thick Beltian series of slightly metamorphosed sedimentary formations and some igneous rocks. They are exposed in broad areas in the Bridger and Little Belt Mountains, in most of the Big Belt Range, and in a few small areas in the Big Snowy Mountains.[10] Most of the Continental Divide and much of its eastern slope from Helena northwestward beyond the International Boundary consists of Beltian rocks. This region is the eastern part of the vast area of Proterozoic sediments in northwestern Montana, northern Idaho, southern Alberta, and British Columbia.

The Beltian series of this region consists mainly of a basal formation of quartzitic sandstone and quartzite and a thick overlying mass of gray, green, and red shale and argillite. This series contains two extensive thick beds of limestone.[11] The beds of shale display abundant mudcracks and many of the thin beds of sandstone are ripple-marked. Casts of salt crystals are reported by Willis from the uppermost formation in Glacier National Park.

Igneous rocks are scarce in this area of Beltian sediments. A few sills and dikes are seen in most extensive sections and one flow is known in Glacier National Park.

Walcott divided the series in the Big Belt Mountains into eight lithologic units, namely, basal Neihart quartzite, Chamberlain shale, Newland limestone, Greyson shale, Spokane shale, Empire shale, Helena limestone, and Marsh shale. Willis subdivided an incomplete section in Glacier National Park into the Altyn limestone (at the base), Appekunny argillite, Grinnell argillite, Siyeh limestone, Sheppard quartzite, and Kintla argillite. Several attempts have been made to correlate the various sections along the Rocky Mountain front and these with others farther west.[12]

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[10] W. R. Calvert, cited by C. D. Walcott: Relations between the Cambrian and Precambrian formations in the vicinity of Helena, Montana. Smithsonian Misc. Coll., vol. 64, no. 4, 1916, p. 274.

O. W. Freeman: New occurrence of the Belt terrane in Montana. Science, vol. 57, 1923, p. 418.

[11] Detailed descriptions are given by C. D. Walcott, Bull. Geol. Soc. Am., vol. 10, 1899, pp. 203-209, and vol. 17, 1906, pp. 1-28; and Bailey Willis, idem., vol. 13, 1902, pp. 316-24.

[12] For correlations, see C. D. Walcott: Bull. Geol. Soc. Am., vol. 17, 1906, pp. 17-21; Joseph Barrell: Jour. Geol., vol. 14, 1906, p. 554; W. H. Emmons and F. C. Calkins; U. S. Geol. Survey Prof. Paper 78, 1913, pp. 35, 36. Edward Sampson made the most recent correlation in a paper before the Geological Society, December, 1926.

At many places the limestone contains numerous algæ and algal reefs,[13] which are especially abundant in the Siyeh limestone in the upper part of the Lewis Range, in Glacier National Park. Similar reefs exist about 100 miles to the south, in the Dearborn Canyon section. Some of the oldest known invertebrate fossils were discovered by Walcott in the Greyson shale in the Big Belt Range.

Walcott estimated the thickness of the Beltian terrane in the Helena-Big Belt Mountain section at about 12,000 feet. Its thickness decreases more than half in the Little Belt Mountains. According to Willis, the incomplete Glacier National Park section is 10,700 feet thick. The series thickens rapidly westward until it is more than 30,000 feet thick in northern Idaho.[14] It may be even thicker to the northwest.

Beltian-Cambrian relations.—Little detailed study has been made of the Beltian-Cambrian contact in the front range other than that of Walcott many years ago. He noted that the basal middle Cambrian sandstone rests on different Beltian formations between Helena and the Big Belt Mountains. The erosion during the Beltian-Cambrian interval amounted to 3,000 or 4,000 feet in the Spokane Hills east of Helena. The same general relation exists to the northwest. Although Calvert[15] reported a pronounced angular unconformity in the Big Snowy Mountains, such a relation is inconspicuous elsewhere in this region. An angular discordance of 30 degrees and beds of Middle (?) Cambrian basal conglomerate were discovered in the Philipsburg Quadrangle, far to the west.[16]

PALEOZOIC

General statement.—Paleozoic formations crop out extensively along the front from Wyoming to within several miles of Glacier National Park. Good sections may be seen in the southern and northwestern parts of the Beartooth Mountains, along the northeast slope of the Little Belt Mountains, at the southeast end and near the northwest end of the Big Belt Range, and in Dearborn Canyon northwest of Helena (figure 5). The Paleozoic rocks are predominantly limestone and shale, but sandstone is common in their basal and upper parts. Their total thickness is about 7,000 feet.

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[13] C. D. Walcott: Precambrian Algonkian algal flora. Smithsonian Misc. Coll., vol. 64, no. 2, 1914.

[14] Edward Sampson: Personal communication, 1927.

[15] Quoted by C. D. Walcott: Smithsonian Misc. Coll., vol. 64, no. 4, 1916, p. 274.

[16] W. H. Emmons and F. C. Calkins: U. S. Geol. Survey Prof. Paper 78, 1913, pp. 50-51, pl. vii.

Cambrian.—Middle and Upper Cambrian rocks occur throughout the region. Walcott[17] in 1908 tentatively reported Lower Cambrian beds from the Continental Divide northwest of Helena, but these beds were later referred to the Middle Cambrian.[18] Hence Lower Cambrian is not known in the Montana ranges. The nearest area in which Lower Cambrian has been certainly identified is in southeastern British Columbia, where a thick section of it is exposed.

With the exception of the lowest formation, the beds consist almost wholly of limestone and shale. Peale[19] defined seven lithologic units in

FIGURE 5.—*Paleozoic Formations on Steamboat Mountain, Coopers Lake Quadrangle*

Beltian strata crop out in the foreground. The ridge crest is Mississippian limestone.

the Three Forks Quadrangle, which can be recognized far to the north and northeast. These formations, as later named by Weed,[20] are the Flathead sandstone (at the base), Wolsey shale, Meagher limestone, Park shale, Pilgrim limestone, Dry Creek shale, and the Yogo limestone. The

[17] C. D. Walcott: Cambrian sections of the Cordilleran area. Smithsonian Misc. Coll., vol. 53, no. 5, 1908, p. 203.

[18] C. D. Walcott: Nomenclature of some Cambrian Cordilleran formations. Smithsonian Misc. Coll., vol. 67, no. 1, 1917.

[19] A. C. Peale: The Paleozoic section in the vicinity of Three Forks, Montana. U. S. Geol. Survey Bull. 110, 1893, pp. 20-25.

[20] W. H. Weed: Geology of the Little Belt Mountains, Montana. U. S. Geol. Survey Ann. Rept. 20, pt. 3, 1900, pp. 284-287.

FIGURE 6.—*Topographic Map of Coopers Lake Quadrangle*

Scale, 1/125,000; contour interval, 100 feet.

boundary between the Middle and Upper Cambrian has been drawn provisionally at the top of the Pilgrim limestone.[21] In the southern part of the region this sevenfold division has not been made, but the lower two formations have been grouped with the Flathead formation and the other five with the Gallatin formation. For northwestern Wyoming, Blackwelder [22] introduced the term Gros Ventre formation, to include the strata between the Flathead sandstone or quartzite and the Gallatin limestone (restricted to the upper beds). Which classification is more applicable to the ranges in southern Montana remains to be determined.

The salient lithologic features of the Cambrian system in this region are the initial sandstone, generally somewhat conglomeratic, but with fragments rarely larger than small pebbles, the marked alternation of shale and limestone, and the universal presence of flat-pebble limestone conglomerate and glauconite in the upper part. The system is less than 1,000 feet thick in the southern part of the region, but is reported by Walcott to be almost 2,700 feet thick in the Big Belt Mountains. Individual formations vary considerably from place to place. The thicknesses in several areas are shown in Table I. The field-work done has not been sufficient to determine the extent and significance of the variations.

TABLE I.—*Approximate maximum Thickness of Cambrian Formations in Montana front Ranges*

Formation	I	II	III	IV	V	VI
Yogo	1,320	450	.....	135	.....	
Dry Creek	150	40	?	80	.....	410
Pilgrim	130	317	340	137	.....	
Park	210	150	290	600	.....	
Meagher	55	400	720	300	300	425
Wolsey	190	420	695	165	750	
Flathead	150	300	640	170	75	
Total	2,205	2,077±	2,685	1,590	1,125	835

I. Dearborn Canyon, Lewis and Clark Range. C. D. Walcott: Smithsonian Miscellaneous Collections, volume 53, number 5, 1908. Formation names were not used by Walcott. The upper part of the so-called Yogo may be younger than Cambrian.

[21] W. P. Haynes: The Lombard overthrust and related geological features. Jour. Geol., vol. 24, 1916, p. 278.

[22] Eliot Blackwelder: New geological formation names in western Wyoming. Jour. Wash. Acad. Sci., vol. 8, 1918, pp. 417-418.

II. Helena district. Adolph Knopf after W. H. Weed: United States Geological Survey Bulletin 527, 1913.

III. Northwestern Big Belt Range. C. D. Walcott: Opus citado, volume 64, number 4, 1916.

IV. Little Belt Mountains. W. H. Weed: United States Geological Survey, 20th Annual Report, part 3, 1900. Minimum thickness, 625± feet.

V. Big Snowy Mountains. C. D. Walcott after W. R. Calvert: Smithsonian Miscellaneous Collection, volume 64, number 4, 1916. Upper formations absent.

VI. Livingston Quadrangle. J. P. Iddings and W. H. Weed: United States Geological Survey Geological Atlas, Folio 1, 1894. Cambrian here is divided into two formations, the Flathead and Gallatin.

Well-preserved Cambrian fossils are not common in this region, but at some places they are abundant and diversified. Walcott[23] lists 32 species of brachiopods and several species of trilobites from Montana.

Ordovician.—The well-known Bighorn dolomite of Wyoming continues northward into Montana as far as the northwest end of the Beartooth Range. Ordovician strata are not known elsewhere in the front ranges. The Bighorn consists of light-colored, slightly fossiliferous dolomite having a peculiar fretted surface, which makes it readily identifiable. It is commonly about 300 feet thick, but it reaches a maximum of 438 feet southeast of Livingston. Tomlinson[24] reports that the lower part is of Trenton and the upper part of Richmond age.

Silurian.—Silurian strata have not been identified in the Montana front ranges. Certain beds between the known Cambrian and Devonian in southwestern Montana have been provisionally referred to the Silurian, but definite proof of their age is lacking. Beds of limestone that were called Silurian in the older reports are now known to belong to the Devonian Jefferson formation. The nearest known Silurian is in southwestern Alberta. It has been recently suggested that a thick deposit of anhydrite below Devonian (?) beds in the Sweetgrass arch, about 75 miles east of the front range in Glacier National Park, may be Silurian.[25] It may perhaps be correlated with similar Upper Silurian strata in Canada.

Devonian.—The type section of the Devonian of Montana was early established in the Three Forks Quadrangle, where the system was divided

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[23] C. D. Walcott: U. S. Geol. Survey Mon. 52, pt. 1, 1912, pp. 114-119.

[24] C. W. Tomlinson: The Middle Paleozoic stratigraphy of the Central Rocky Mountain region. Jour. Geol., vol. 25, 1917, pp. 126, 127.

[25] A. J. Collier: The Kevin-Sunburst oil field, Montana. U. S. Geol. Survey Press Bull., January 12, 1926.

into the Jefferson formation and the overlying Three Forks shale.[26] Because of its extensive and interesting fauna, the shale has been studied in detail in that district.[27] Kindle[28] has summarized the meager knowledge of the Jefferson formation in Montana. Both formations have been examined in several areas, but few details are known in the front ranges. Sections have been reported from the Beartooth[29] and Little Belt mountains.[30]

The Jefferson formation consists chiefly of magnesian limestone and so-called dolomite, characterized by a dominance of dark grayish brown to black beds that have a strongly fetid odor on fresh fracture. Its thickness is 200 feet in the Big Snowy Mountains,[31] more than 400 feet near Livingston, more than 600 feet at Logan, and about 1,000 feet in the Philipsburg Quadrangle, where the maximum known section exists. Sections have not been measured in the Big Belt Mountains or in the front range northwest of Helena. Fossils are generally scarce, but in some places are fairly numerous. Kindle reports 22 species from Montana. The faunas indicate that the formation is Lower (?) and Middle Devonian.

The Three Forks formation in the type area consists of beds of shale—mainly black, yellow, orange, and green—and intercalated beds of limestone. The formation appears to become more argillaceous toward the north and more calcareous toward the south. In much of the region the orange and black shales are rather distinctive. Some of the beds are highly fossiliferous. The faunas are late Devonian, the uppermost strata being the youngest Devonian on the continent. The formation is about 350 feet thick in the Three Forks area, but decreases toward the front ranges until it is much thinner or even disappears.

Carboniferous.—The Carboniferous beds consist mainly of the Madison limestone and the Quadrant formation. The Phosphoria formation is present in the southern part of the region. The Madison limestone is

[26] A. C. Peale: U. S. Geol. Survey, Bull. 110, 1893, p. 27.

[27] P. E. Raymond: On the occurrence in the Rocky Mountains of an upper Devonian fauna with Clymenia. Am. Jour. Sci. (4), vol. 23, 1907, pp. 116-122. Also, The fauna of the upper Devonian in Montana. Ann. Carnegie Mus., vol. 5, 1909, pp. 141-158.

W. P. Haynes: The fauna of the upper Devonian in Montana. Part 2, The stratigraphy and the Brachiopoda. Ann. Carnegie Mus., vol. 10, 1916, pp. 13-54.

[28] E. M. Kindle: The fauna and stratigraphy of the Jefferson limestone in the northern Rocky Mountain region. Bull. Am. Paleont., vol. 4, no. 20, 1908.

[29] J. P. Iddings and W. H. Weed: U. S. Geol. Survey Geol. Atlas, Folio No. 1, 1894. C. W. Tomlinson: Jour. Geol., vol. 25, 1917, p. 380.

[30] W. H. Weed: Geology of the Little Belt Mountains, Montana. U. S. Geol. Survey, 20th Ann. Rept., pt. 3, 1900, pp. 287-289.

[31] A. J. Ellis and O. E. Meinzer: Ground water in Musselshell and Golden Valley counties, Montana. U. S. Geol. Survey Water-Supply Paper 518, 1924, p. 14.

boldly exposed in all the front ranges south of Glacier National Park (figure 7). Weed[32] divided it in the Little Belt Mountains into three members: Paine shale (below), Woodhurst limestone, and Castle limestone The Paine shale consists of thin-bedded, impure limestone and calcareous shale. Rather thick, well-bedded limestone forms the middle member. The Castle limestone is characterized by extremely massive beds, which in many areas form huge cliffs (figure 8). Although recognizable in most or all of the front ranges, these divisions have generally

FIGURE 7.—*North-south Thrust-blocks across Sun Canyon*

Each ridge consists mainly of Mississippian limestone. Mesozoic sediments exist in the valleys.

not been made. Many of the beds appear to be barren or but slightly fossiliferous, but at certain horizons fossils are extremely abundant and diverse. The Madison is commonly between 1,000 and 2,000 feet thick, but is reported to be 2,600 feet thick near Helena.

The typical Madison is of early Mississippian age. It has been suggested that the upper part in the Lewis and Clark Range[33] corresponds to the Brazer limestone of northern Utah, which, according to Girty, is

[32] U. S. Geol. Survey, 20th Ann. Rept., pt. 3, 1900, p. 290.

[33] Eugene Stebinger: Oil and gas geology of the Birch Creek-Sun River area, northwestern Montana. U. S. Geol. Survey Bull. 691, 1918, p. 155.

basal upper Mississippian. In most of the ranges the Madison has not been sufficiently studied to determine its faunas and divisions.

The Madison limestone is overlain by the Quadrant formation from the Wyoming line northward to the Little Belt Mountains. The Quadrant is not known farther northwest and appears to be absent in northwestern Montana. It consists mainly of marine sandstone, shale, and subordinate limestone. Some of the beds of shale are vivid green and

FIGURE 8.—*West Slope of front Ridge of Mississippian Limestone*

The locality is at the mouth of Sun Canyon, Saypo Quadrangle.

red. Fossils of both upper Mississippian and lower Pennsylvanian age have been found in the formation in widely separated districts. It is not certain whether these fossils were collected from the same formation. The formation ranges in thickness from a few hundred to more than 1,000 feet.

The youngest Paleozoic formation is the Phosphoria, which is Permian. Condit[34] mapped it in the Beartooth Range, but it appears to be thin or absent in the remainder of the front ranges. It is probably about 100 feet thick.

[34] D. D. Condit: Relations of the late Paleozoic and early Mesozoic formations of southwestern Montana and adjacent parts of Wyoming. U. S. Geol. Survey Prof. Paper 120, 1918, pl. ix.

MESOZOIC

General statement—Mesozoic sediments are found at but few places in the front ranges, although they are widespread in the foothills and on the adjoining plains. The sediments are preponderantly clastic and represent all systems. Their total maximum thickness, including the so-called Fort Union, is about 18,000 feet.

Triassic.—The main belt of Triassic rocks along the mountain front is near the Wyoming boundary, where the Chugwater Red Beds encircle the Bighorn and Pryor Mountains and crop out along the southeastern side of the Beartooth Range. The Chugwater continues under cover to the Big Snowy Mountains, where it is again exposed.[35] The thickness in Montana is less than 500 feet. Marine Triassic is found west of Yellowstone Park, but the embayment appears not to have extended to the site of the Montana front ranges.

Jurassic.—Upper Jurassic only is present. The Ellis formation, which consists of marine calcareous sandstone, shale, and some limestone, crops out across the State. Some beds are highly fossiliferous. The Ellis occurs on the flanks of all the ranges and is probably present well within the frontal ridge of the Lewis and Clark Range. Its thickness in this part of Montana varies from less than 100 to about 450 feet.

Pre-Ellis unconformity.—The Ellis rests disconformably on Triassic and late Carboniferous strata and cuts across gently tilted Madison limestone south of Great Falls. Condit[36] discovered an extensive marked angular unconformity at its base west and north of Yellowstone Park. Collier[37] recently summarized the relations between the Ellis and the Madison on the northern plains. The Ellis overlaps formations from Triassic in Wyoming to Devonian in northern Alberta.

Cretaceous.—The basal Lower Cretaceous is the Morrison formation, which appears in places along the front ranges to the northwest end of the Little Belt Mountain. It consists of varicolored, nonmarine clastics about 100 to 200 feet thick. The overlying Kootenai is a widespread formation composed of continental clastics, among which maroon beds and a thick, persistent basal conglomerate of chert pebbles are prominent. This conglomerate has a notable significance as to the conditions prevailing in the region of its source. The Kootenai contains coal on the plains of northern Montana, but not in the front ranges south of Alberta.

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[35] Paul Billingsley: Sweet Grass Hills, Montana. Bull. Geol. Soc. Am., vol. 32, 1921, p. 467.

[36] Idem, p. 120.

[37] A. J. Collier: The unconformity between the Madison limestone and Ellis formation in northern Montana. Jour. Wash. Acad. Sci., vol. 17, 1927, pp. 130-131.

its thickness ranges from about 350 to 1,000 feet, increasing toward the northwest.

The typical marine Colorado shale is conspicuous in the foothills of all the ranges and crops out in the frontal ridge of the Lewis and Clark Range. Intercalated beds of sandstone are locally prominent. The Colorado is about 1,800 to 3,700 feet thick. Next above is the Montana group, composed of Eagle sandstone (at the base), Claggett shale, Judith River formation, and Bearpaw shale. This group is almost 3,000 feet thick in the outer foothills along the northern ranges. The formations grade from marine on the outlying plains to continental toward the mountains. On the northwestern plains the continental strata between the lower Eagle (Virgelle) sandstone and the Bearpaw shale form the Two Medicine formation.[38] It is about 2,000 feet thick. The uppermost formation, commonly regarded as Cretaceous, is a sandstone, known as Horsethief sandstone north of Dearborn River and Lennep sandstone in the vicinity of the Crazy Mountains. This formation is 250 to 400 feet thick.

Lying on the plainsward flank of the northern half of the Beartooth Range and surrounding the Crazy Mountains is a series of tuffaceous shale and sandstone and a thick median wedge of volcanic agglomerate. This series of beds is called the Livingston formation. It is over 5,000 feet thick and it represents a lateral gradation eastward from volcanic to normal sediments during early Montana to early Fort Union time.[39]

The youngest sediments immediately adjacent to the front ranges are found in broad synclines east of the Lewis and Beartooth ranges. In the Beartooth Range the so-called Fort Union formation (possibly including the Lance) consists of about 8,500 feet of continental clastics and several workable coal beds. East of the Lewis Range about 1,700 feet of the Saint Mary River and Willow Creek nonmarine sandstones and shales overlie the Horsethief sandstone without perceptible break. The age of the Lance and Fort Union has long been a moot question. The prevailing view until lately has been that they are early Eocene (?), but recent opinion makes them latest Cretaceous.[40]

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[38] Eugene Stebinger: The Montana group of northwestern Montana. U. S. Geol. Survey Prof. Paper 90, 1914, p. 63.

[39] R. W. Stone and W. R. Calvert: Stratigraphic relations of the Livingston formation of Montana. Econ. Geol., vol. 5, 1910, 551-557, 653-669, 741-764.

[40] Charles Schuchert: Historical geology, 1924, pp. 564, 565; also p. 581 for references. W. T. Thom and C. E. Dobbin: Stratigraphy of Cretaceous-Eocene transition beds in eastern Montana and the Dakotas. Bull. Geol. Soc. Am., vol. 35, 1924, pp. 481-506. Eugene Stebinger: Op. cit., p. 68.

CENOZOIC

If the Lance and Fort Union formations are Cretaceous, the only Cenozoic sediments along the mountain front are terrace gravels, alluvium, and glacial drift. The terrace gravels, which appear to range in age from Pliocene to Recent, cover broad benches at several levels. Alden [41] has shown that the drift was deposited by huge valley glaciers during two and probably three stages.

The intermontane valleys on the west and southwest flanks of the Bridger, Little Belt, and Big Belt Mountains are partly filled with thick masses of clastic sediments and intercalated volcanic ash. These beds are of Oligocene and Miocene age.

IGNEOUS ROCKS

Except in the pre-Cambrian terranes, pre-Cretaceous igneous rocks are extremely rare or absent in the front ranges. The Livingston tuffaceous beds and agglomerate of the Beartooth and Crazy Mountains have been mentioned. Lavas were extruded in the northwestern Big Belt Range during late Cretaceous (?) and early Tertiary time. Volcanic breccias and tuffaceous sediments accumulated more or less concurrently along the mountain front between Dearborn River and Missouri River near Wolf Creek. Intrusion and extrusion formed outlying mountain groups during Tertiary time and scattered masses of intrusives then invaded the frontal zone. The Boulder batholith [42] invaded a vast area west of the front ranges during late Cretaceous or early Tertiary time. Peripheral bosses affected to some extent the frontal zone, notably in the Big Belt Range. The intrusions in the Lewis and Clark Range may be essentially contemporaneous, but they have not been studied in detail.

STRUCTURE

GENERAL STATEMENT

The main belt of the front ranges may be divided somewhat roughly into five structural zones (figure 1). From north to south they are: (1) the Lewis overthrust and associated structures; (2) the Lewis and Clark zone of overthrust slice blocks; (3) the Little Belt-Big Snowy anticlinorium; (4) the Bridger anticline; and (5) the Beartooth anticline and overthrust. Two other zones appear to be closely related to the

[41] W. C. Alden: Physiographic development of the northern Great Plains. Bull. Geol. Soc. Am., vol. 35, 1924, pp. 385-424.

[42] Paul Billingsley: The Boulder batholith of Montana. Trans. Am. Inst. Min. Eng., vol. 51, 1916, pp. 31-56.

main ranges, namely, the Big Belt anticline and certain isolated groups, such as the Judith, Castle, and Crazy Mountains, just beyond the mountain front.

LEWIS OVERTHRUST ZONE

The Lewis overthrust has been adequately discussed by Willis[43] and is so well known that details need not be given here. This zone is characterized by a major low-angle overthrust along the base of the steep mountain front, which has been traced more or less continuously from a point far north of the International Boundary to the southern end of Glacier National Park. The measurable eastward displacement is at least 15 miles, and the actual displacement is undoubtedly considerably greater. It thrust a huge block of Beltian and superincumbent strata over late Cretaceous formations. The Lewis overthrust is bordered on the east by a "belt of disturbed rocks" in which the strata have been considerably warped and broken along their strike by high-angle thrust-faults.[44] This disturbed belt is reported to be more than 200 miles long and to have a width of 20 miles east of Glacier National Park.

The southern extension of the Lewis overthrust is one of the unsolved problems of the northern Rockies. Campbell[45] has mapped it to the south border of Glacier National Park, where the trace is about 5 miles west of the Continental Divide and about 20 miles west of the mountain front. Stebinger[46] states that the Lewis overthrust lies west of the front range, south of Glacier National Park. Emmons and Calkins,[47] in their study of the overthrusts in the Philipsburg Quadrangle, suggested a possible continuity of the Lewis and Philipsburg thrust-zones. Ransome[48] questions this interpretation because of the structural trends and the extent of unexplored territory. Until more field-work has been done south of Glacier National Park, the southern continuation of the Lewis overthrust must be conjectural.

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[43] Bailey Willis: Stratigraphy and structure, Lewis and Livingston ranges, Montana. Bull. Geol. Soc. Am., vol. 13, 1902, pp. 305-352.

[44] Eugene Stebinger: Geology and coal resources of northern Teton County, Montana. U. S. Geol. Survey Bull. 621, 1916, p. 129.

J. S. Stewart: Geology of the disturbed belt of southwestern Alberta. Can. Geol. Survey, Memoir 112, 1919.

[45] U. S. Geol. Survey Bull. 600, 1914, plate xiii.

[46] U. S. Geol. Survey Bull. 691, 1918, p. 172.

[47] U. S. Geol. Survey Prof. Paper 78, 1913, p. 146.

[48] F. L. Ransome: The Tertiary orogeny of the North American Cordillera and its problems. In "Problems of American Geology." Yale Univ. Press, 1915, p. 312.

ZONE OF OVERTHRUST SLICE BLOCKS

Southeast of Glacier National Park the front range is bounded by overthrusts, which have carried huge blocks of Madison limestone well up and over Cretaceous sediments. The topographic contrast produced by this zone of faults is clearly shown on the Coopers Lake and Saypo topographic maps northwest of Dearborn Canyon (figures 4 and 6). South of Dearborn River the fault-zone is concealed by a belt of volcanic rock, which extends to Missouri River. Although this fault-zone can not be traced in this area, the extrusion of the lavas and the existence of a zone of faults in alignment with it along the northwest end of the Big Belt Range indicate its presence.

The Lewis and Clark Range north of Dearborn Canyon consists of a series of north-south subparallel ridges and narrow valleys (figures 3, 4, and 6). With only one known exception, each ridge appears to be a westward-dipping block of Mississippian limestone overthrust eastward on Mesozoic sediments (figures 7 and 8). Jurassic and Cretaceous formations lie on the lower western flanks of most or all of the fault-blocks. A rapid reconnaissance of Sun River Canyon and a few of its tributaries shows that at least seven and possibly ten of these thrust-blocks lie athwart Sun River. These faults dip more steeply than the Lewis overthrust. The structure in this zone consists of a series of overlapping plates which are more or less of the "Decken" type. The number of slices decreases to the north and to the south. Studies have not been made north of Sun River. The throw of the faults decreases to the south; hence most of the faults disappear in a disturbed belt of Jurassic and Cretaceous strata, until apparently only a single zone of faults continues southward across Dearborn River (figure 6). In this southern zone Beltian and Cambrian are thrust over Jurassic and Cretaceous rocks. As a result of this structural change, the bold ridges of Mississippian limestone in the Saypo Quadrangle successively disappear southward, producing an *en echelon* pattern.

The formations east of the mountain front are less faulted in this zone than in front of the Lewis overthrust on the north. They are compressed into a series of closely spaced gentle and sharp folds, which are broken in places by steep thrust-faults that are roughly parallel to the strike.

The zone of overthrust slice blocks in the Lewis and Clark Range has three possible interpretations: (1) The Lewis overthrust has been distributed in a series of smaller steeper thrusts south of Glacier National Park; (2) the main overthrust is far within the range and is flanked

on the east by a series of thrusts (limestone blocks) analogous to those in the disturbed belt east of the Park; or (3) the Lewis overthrust continues southward along the front range as a "sole," the huge limestone blocks being slices in the main overthrust mass. It may be that the Lewis overthrust south of the Park splits into more than one sole. In any case, it seems probable that the structure resembles the Scottish Highlands type in at least part of this zone. Detailed field study will be necessary to solve these problems.

BIG BELT ANTICLINE

The Big Belt Range is structurally a large anticline that trends southeastward from Missouri River, about 25 miles north of Helena, almost to the north end of the Bridger Range. It is aligned with and is the continuation of the main structural axis of the front ranges between the Lewis and Clark and Bridger ranges (figure 1). This relation is obscured by the prominent eastward salient formed by the Little Belt-Big Snowy anticlinorium.

Rapid reconnaissance of much of the range by the writer and detailed work done by others in bordering areas indicate the existence of certain structural features. The main mass of the range consists chiefly of the Beltian terrane, which apparently covers an outlying portion of the Boulder batholith. Outcrops of a granitoid intrusion are scattered along the crest of the range. Mesozoic, Paleozoic, and Beltian strata on the flanks of the range are broken in several places by faults.

The northwest end of the Big Belt Range appears to be bounded by a considerable thrust-fault or zone of faults. Several features warrant this interpretation. Near the mouth of Beaver Creek, an east tributary of Missouri River about 20 miles northeast of Helena, Paleozoic formations, including the Madison limestone and possibly the Quadrant formation, dip steeply to the west. According to Billingsley's map of the Boulder batholith, Beltian rocks crop out across the Missouri to the west. Several miles to the northwest, east of the town of Wolf Creek, Cretaceous strata are exposed a few miles east of the main Beltian mass. The relations are concealed by volcanic rock, but the areal distribution and the structure of these formations imply an intervening fault, which is probably a thrust-fault.

It is tentatively concluded, therefore, that a zone of thrust-faults exists along the northwest side of the range. Furthermore, it is inferred that this fault-zone is either the southward continuation of the fault-zone that disappears beneath the volcanic rock southeast of Dearborn Canyon or is intimately related to it.

Little is known of the structure of the range farther south, except that the Paleozoic beds are sharply folded and broken by faults, until the Lombard overthrust is reached, on Missouri River, near the southwest end of the range. This overthrust was discovered by Haynes,[49] who found that Beltian rocks near Lombard have been thrust eastward until they lie on Cretaceous beds. The throw decreases toward the southwest, so that Upper Cambrian comes into contact with Madison limestone. The fault surface dips about 40 degrees to the west. Pardee[50] has recently mapped some normal faults along the west base of the range, north of the Lombard overthrust, which cut the Tertiary intermontane sediments. Undoubtedly there are other normal faults.

Although speculation is hazardous, and perhaps somewhat unwarranted with such meager information, it may be suggested as a working hypothesis that the Lombard overthrust is more or less closely related to the fault-zone that extends southeastward from Glacier National Park past the northwest end of the Big Belt Range. The Lombard fault curves northward after crossing the horseshoe bend of Missouri River, and apparently passes under Tertiary sediments on the east side of Townsend Valley. It may continue beneath this Tertiary cover directly into the northern fault-zone or it may branch off in that direction.

The Big Belt and Little Belt ranges converge at the north, toward Missouri River (figure 1). The intermediate area contains numerous subparallel faults of southeasterly trend, some or most of which are thrusts. These faults are most abundant and of greatest displacement along the northeastern flank of the Big Belt Range. The northwest end of the plunging Little Belt anticline appears to be only slightly faulted. As these faults converge to the northwest, it appears that this zone may be the southeastern extension of that between Dearborn and Missouri rivers.

One of the main faults is shown on the Little Belt Mountains geologic map (Folio 56). It is a thrust-fault along the southwestern slope of the Little Belt Mountains, which brings Beltian strata (on the southwest) in contact with Madison limestone. As mapped, this fault disappears before the plains are reached. The folio map shows a parallel fault about 15 miles to the southwest, along the northwest side of Castle Mountains, which causes Beltian to abut against Cretaceous. This fault is concealed to the northwest by Tertiary intermontane deposits. An-

[49] W. P. Haynes: The Lombard overthrust and related geological features. Jour. Geol., vol. 24, 1916, pp. 269-290.

[50] J. T. Pardee: Geology and ground-water resources of Townsend Valley, Mountain. U. S. Geol. Survey Water-Supply Paper 539, 1925, p. 16.

other fault is shown about 20 miles farther southwest, along the northeast end of the Bridger Range. It has the same general trend and relations.

Hence it is suggested that an overthrust zone extends southeastward along the mountain front from Dearborn Canyon to Missouri River, where it again breaks into a number of thrust-plates. Some of the distributive faults are on both flanks of the Big Belt Range. Another group of faults may branch off, as tentatively suggested by Thom,[51] to connect with the great overthrust in the Philipsburg district.

LITTLE BELT-BIG SNOWY ANTICLINORIUM

The Little Belt and Big Snowy Mountains are asymmetrical anticlines that constitute a marked plainsward salient in the general northwesterly trend of the front ranges. The Little Belt uplift trends obliquely outward from the main front zone into the Big Snowy uplift, which has an east-west axis. This uplift has been called the Big Snowy anticlinorium,[52] but the grouping of the two uplifts into one structural zone seems to be justified. The axis of this anticlinorium continues across central Montana through a series of sharp asymmetrical anticlines. Thom[53] has recently examined and interpreted the relations in this zone. He states that this dispersion of the Rocky Mountain backbone occurred "probably because the edge of the overthrust sheet . . . impinged against older east-west uplifts and was disrupted by them." Rotation of fault-blocks in the basement terrane probably in part produced the form of the individual structural units.

BRIDGER ANTICLINE

The Bridger Range is a north-south anticline, which continues southward the main axis that passes through the Big Belt Range. It has not been studied in detail and nothing has been published on it since the early geologic folios (numbers 1 and 24) on this region. The maps and descriptions in these folios show that this anticline is strongly overturned to the east and has a relatively gentle western flank. Minor faults only are shown. The areal relations of the formations as mapped and the position of the range between the severely deformed zones to the northwest and southeast suggest that detailed work might reveal other faults, or at least might help to decipher more clearly the relations of this uplift

[51] W. H. Thom: The relation of deep-seated faults to the surface structural features of central Montana. Bull. Am. Assoc. Petrol. Geol., vol. 7, 1923, p. 3, figure 1.

[52] C. T. Lupton and Willis Lee: Bull. Am. Assoc. Petrol. Geol., vol. 5, 1921, pp. 252-275.

[53] Op. cit., pp. 1-13.

to other front range structures. Iddings and Weed[54] state that the anticline "is overthrown at the south end, where gneisses and schists rest on inverted Paleozoic strata." This relation suggests strongly that thrust-faults may exist here.

BEARTOOTH ANTICLINE AND OVERTHRUST

The writer[55] has determined the broader structural features of the Beartooth Range, but has not intensively studied many of its details. In brief, the range is a huge anticline overturned strongly toward the plains and broken by a large thrust-fault, the Beartooth overthrust. This fault has been traced from Clark Fork, at the south end of the range, almost to Livingston. South of the Montana line Archean crystalline rocks lie on Mesozoic formations. In a few places the Paleozoic section is completely cut out. Along most of the range Madison limestone is thrust against Fort Union or Livingston strata. The displacement decreases to the northwest and the main fault seems to break into several smaller faults southeast of Livingston. The actual fault surface has not been observed, but it dips at an angle so high that its trace is only slightly embayed across major valleys.

The Beartooth fault-zone has not been traced west of Boulder Valley southeast of Livingston. Calvert[56] mapped anticlinal axes and a fault that trend northwestward through an area about 12 miles southwest of Livingston. These structures may be an extension of the Beartooth fault-zone.

The southwest slope of the Beartooth Range is faulted at several places. A zone east of Yellowstone Valley above Livingston is shown on the Livingston geologic map (Folio 1). The writer discovered another zone east of the upper Clark Fork River, in northern Wyoming. These faults seem to be of the gravity type. The alignment of intrusions and the enormous mass of volcanic rocks in the neighboring Absaroka Range, to the southwest, suggest the existence here of a concealed fault-zone that is roughly parallel to the axis of the Beartooth Range.

SUMMARY OF THE STRUCTURE

The above brief preliminary description of the structural elements of the front ranges shows that this Rocky Mountain lineament is every-

[54] U. S. Geol. Survey Geol. Atlas, Folio No. 1 (Livingston), 1894, p. 1.

[55] Arthur Bevan: Summary of the geology of the Beartooth Mountains, Montana. Jour. Geol., vol. 31, 1923, pp. 441-465.

[56] W. R. Calvert: The Livingston and Trail Creek coal fields. . . . Montana. U. S. Geol. Survey Bull. 471, 1912, plate xxix.

where overfolded or overthrust toward the Great Plains from far north in Alberta across Montana into northern Wyoming. In places there are comparatively simple low-angle overthrusts; in others there is a single high-angle thrust, and in still others there is a series of thrust-plates bounded by moderately steep faults. The magnitude of the displacements, both horizontally and stratigraphically, varies within wide limits. The maximum known horizontal movement exceeds 15 miles for the Lewis overthrust and approaches 30 miles for the Heart Mountain overthrust in northern Wyoming. It may be only a small fraction of this distance for some of the other faults. The greatest stratigraphic offset brings Archean against late Cretaceous.

AGE OF THE DEFORMATION

Little can be done beyond what has been published to determine the time of deformation, but the data available may be briefly summarized.

Sediments of late Cretaceous age are folded or faulted in or along all the front ranges. The Beartooth Range was folded and faulted after the deposition of the Fort Union formation. The Beartooth overthrust is regarded as essentially contemporaneous with the Heart Mountain overthrust of northwestern Wyoming, which Hewett[57] considers post-middle Bridger (Eocene) and probably not later than early Oligocene. The upper part of the Livingston formation (Fort Union) along the east side of the Bridger Range includes a thick conglomerate containing pebbles of Paleozoic limestone and pre-Cambrian granite.[58] Erosion on the southwest flank of the Bridger Range widely uncovered pre-Cambrian rocks prior to the deposition of the Miocene Bozeman "lake beds." Some of the faults along the Belt ranges pass under Oligocene and Miocene intermontane deposits, which contain much material derived from the Paleozoic and Beltian formations of the ranges. Haynes regards the Lombard overthrust as very late Cretaceous or early Tertiary. The thrust-blocks of the Lewis and Clark range rest on latest Cretaceous or early Eocene formations. It has been stated that the Lewis overthrust is of late Eocene or early Oligocene age.[59] The major deformation in Alberta, according to Stewart, is post-Fort Union and it seems to be certainly pre-Oligocene.

It has been supposed that the intrusion of the Boulder batholith and

[57] D. W. Hewitt: The Heart Mountain overthrust. Wyoming. Jour. Geol., vol. 27, 1920, pp. 536-557.

[58] W. H. Weed: Laramie and Livingston formations in Montana. U. S. Geol. Survey Bull. 105, 1893, p. 31.

[59] G. R. Mansfield: Bull. Geol. Soc. Am., vol. 34, 1923, p. 269.

of some of the outlying igneous masses was a result of the stresses of this diastrophic cycle. These intrusions have been interpreted as of Tertiary age.[60]

Although detailed field study of this major problem has not been made for much of the frontal belt, the conclusion seems warranted that the greater part of the profound deformation of the Montana front ranges occurred in a series of movements in a single great diastrophic cycle, commonly called the Laramide Revolution. This series of orogenic movements appears to have begun in late Cretaceous and to have culminated in early (?) Eocene time. The diastrophism was probably not continuously of the same intensity throughout the entire belt; it rather consisted of a series of movements that affected different zones as stresses accumulated and were transmitted through these zones. The overfolds and thrust-faults may, therefore, not be strictly contemporaneous, even in a geologic sense, but they are probably rather intimately related as offspring of a common dynamic parentage.

Although the Cordilleran region west of the geosyncline from which the front ranges were formed was uplifted considerably at intervals during late Paleozoic and Mesozoic time, little, if any, severe deformation seems to have occurred in the frontal belt until near or at the end of the Mesozoic era. A possible exception is the east-west anticlinorial axis of the Little Belt and Big Snowy Mountains, which, as suggested by Thom,[61] may antedate the main uplift of the northwest-southeast belt of front ranges.

Outline of History

The Archeozoic history of the region comprised a series of events whose relations are largely unknown, but it included great vulcanism, deformation, and metamorphism. After a long period of erosion, the vast Beltian series was deposited in the gradually subsiding Proterozoic Cordilleran geosyncline. These sediments probably record oscillations between marine, deltaic, and continental conditions.[62] In late Proterozoic time the region was broadly upwarped, and the uplift caused widespread and deep erosion before the ingress of the sea in middle Cambrian time.

The Paleozoic record is one of fluctuating seas. The front range portion of the Cordilleran trough was invaded by marine waters during the middle and late Cambrian, the middle and late Ordovician, the early

[60] Paul Billingsley: The Boulder batholith of Montana. Trans. Am. Inst. Min. Eng., vol. 51, 1916, p. 35.

[61] W. T. Thom: Bull. Am. Assoc. Petrol. Geol., vol. 7, 1923, pp. 1-23.

[62] Joseph Barrell: Precambrian formations of Montana. Jour. Geol., vol. 14, 1906, pp. 553-560.

(?), middle, and late Devonian, the early and late Mississippian, part of the Pennsylvanian, and part of the Permian. Whether the seas occupied the entire geosyncline in Montana during all these epochs, whether portions of this trough were flooded during other epochs, and how long the seas remained, are still largely conjectural. These problems can not be settled until more detailed study has been made of the stratigraphy and faunas of the general region. The calcareous nature of much of the sediment and the fine grain of most of the clastic material suggest that the epeiric seas were broad and that the bordering lands had low relief most of the time. Desert conditions may have prevailed in the northern part of the region during late Silurian time.

During late Paleozoic and early Mesozoic time the region appears to have been broadly affected by rather marked uplifts, which resulted in local unconformities and basal conglomerates, and finally in the peneplanation of at least southern Montana before late Jurassic time.

Whether the Triassic Pacific seas reached this region is also unknown. During this period, and perhaps also early in the Jurassic, conditions favorable to the deposition of extensive red beds existed from Wyoming northward into Montana. During the remainder of the Mesozoic era shallow seas alternated with broad coastal plains and river floodplains. At times, especially early in the Cretaceous period, the landmass to the west was so strongly elevated that the later Paleozoic formations were deeply eroded and their more resistant constituents were transported as gravel into the eastern part of the depositional basin. Recurrent uplifts or cyclic alternation of climates are suggested by the presence of gravel in most of the Mesozoic formations.

In late Cretaceous and early Tertiary time, during the Laramide Revolution, the whole region was profoundly deformed. The exact sequence of the times of folding and faulting remains to be determined. The deformation appears to have begun on the west and to have moved eastward. The front ranges probably were affected by a series of deformational waves, which were components of the major revolution. During this revolution huge intrusions and considerable extrusion occurred. Premonitory indications of this vulcanism seem to have appeared in Cretaceous time.

The post-Laramide events of the region consisted of a series of erosion cycles and broad vertical uplifts. During Tertiary time considerable part if not most of the front ranges was reduced to moderate relief or generally peneplaned at least once (see figure 2) and possibly twice. Marked uplift occurred in late Pliocene or early Quaternary time (see

figures 2 and 8). The higher ranges were severely glaciated during two or more stages.

Summary

The geology of the front ranges of the Rocky Mountains in Montana is provisionally outlined. Some of the numerous problems that await detailed field study are suggested.

The front ranges consist of seven orographic units. The Beartooth, Bridger, Big Belt, Lewis and Clark, and Lewis ranges form a belt having a distinct northwesterly alignment. A broad plainsward salient is formed in the middle of this belt by the Little Belt and Big Snowy Mountains. Several outlying ranges, such as the Crazy and Judith Mountains, are probably closely related to the main belt.

Each of these ranges rises abruptly from the Great Plains for a few thousand feet. Some have remarkably steep fronts. In a few of them the accordance of summit levels is impressive.

The indurated rocks of the front ranges are Archean, Proterozoic, Paleozoic, and Mesozoic. With the exception of the Archean crystallines, they are almost wholly sedimentary and have a total thickness of at least 37,000 feet. Lower Cambrian and Silurian rocks are unknown. The post-Proterozoic igneous rocks are of Cretaceous and Tertiary age. Marked unconformities exist at the base and top of the Proterozoic and at the base of the upper Jurassic. Disconformities are numerous.

The structure may be briefly characterized as a series of thrusts and folds, overturned toward the Great Plains. Five structural zones are recognized. One of the most striking is a zone of thrust slices south of the Lewis overthrust belt along Glacier National Park. The Lewis, Lombard, Beartooth, and intervening faults appear to form an almost continuous belt across Montana.

The history of the front ranges has been that of a great geosyncline subject to repeated invasions and retreats of the sea from Proterozoic into Cretaceous times. Continental sedimentation became increasingly important through the Mesozoic era. Parts of the region were rather prominently emergent during late Paleozoic and early Mesozoic time. Uplands having considerable relief existed to the west during at least a part of the Cretaceous period. During the Laramide Revolution the huge geosynclinal prism of sediments was converted into the principal structures of the present front ranges. Thrust-faulting occurred on a grand scale. Igneous intrusions and subordinate extrusions were formed more or less concurrently. The Cenozoic history has been chiefly a series of erosion cycles related to a series of vertical uplifts and interrupted by two or more stages of glaciation.

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COMANCHEAN REPTILES FROM KANSAS, OKLAHOMA, AND TEXAS[1]

BY CHARLES N. GOULD

(Presented before the Society December 28, 1928)

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COMANCHEAN CLASSIFICATION

According to the classification made by Hill, the Comanchean, or Lower Cretaceous, series in Texas and southern Oklahoma is divided into the Trinity, Fredericksburg, and Washita groups. In southwestern Kansas the Comanchean consists of the Cheyenne sandstone and Kiowa shales. The Kiowa formation, containing a Kiamichi fauna, is regarded by Bullard[2] as of Washita age.

FIRST DISCOVERIES

The first record of the discovery of Comanchean dinosaur bones that I have been able to find is that made by R. T. Hill.[3] The bones were found in the basal Trinity near Lambert, Parker County, Texas, some 35 miles west of Fort Worth. These bones, however, were not the first discovered. In a letter from Doctor Hill dated December 9, 1928, he says: "I found a saurian tooth in the Lower Comanchean near Comanche

[1] Manuscript received by the Secretary of the Society January 7, 1929.

[2] Fred M. Bullard: Lower Cretaceous of western Oklahoma. Oklahoma Geol. Survey, Bull. 47, 1928, p. 61.

[3] R. T. Hill: The topography and geology of the Cross Timbers and surrounding regions in northern Texas. Amer. Jour. Sci., 3d ser., vol. 33, 1887, p. 298. Also, Geography and geology of the Black and Grand Prairies, Texas. U. S. Geol. Survey, 21st Ann. Rept., pt. 7, 1901, p. 192.

when I was a boy. It was taken to Cornell with me." This tooth was probably discovered in the late seventies.

Kansas Reptiles

The Kansas Comanchean, consisting chiefly of the Cheyenne sandstone and the Kiowa shales, has yielded a number of reptilian forms. These formations are exposed chiefly in Kiowa and Clark counties, in southwestern Kansas. In 1894 Cragin[4] described several new species of vertebrates, including *Plesiosaurus mudgii*, a fossil turtle, and two fossil sharks, collected from the Kiowa shales of the Belvidere region, southern Kiowa County, and from Bluff Creek, Clark County.

In the same year I discovered and sent to Doctor Williston,[5] then at Kansas University, a number of bones collected in northern Clark County, among which he identified two fossil fishes, a turtle, a crocodile, and a new species of plesiosaur belonging to the genus *Cimoliosaurus*.

A few years later I discovered in these shales the bones of a new species of plesiosaur, which Williston in 1897 named *P. gouldii*.[6]

I know of no search made for reptilian bones in the Kansas Comanchean for thirty years. During this time the soft Kiowa shale containing these fossils has, no doubt, been eroded, and rich finds probably await the collector in Kiowa and Clark counties.

An Oklahoma Dinosaur

Only one specimen of Comanchean reptile has been reported from Oklahoma. In 1909 Mr. Pierce Larkin, then a student at the University of Oklahoma, discovered part of a morosaurian coracoid in an upper bed of the Trinity sandstone south of Atoka. This fossil was described by Williston as "the first indisputable evidence of the occurrence of sauropod dinosaurs in the Cretaceous of western America."[7]

Dinosaur Tracks in Texas

In addition to the dinosaur bones found long ago in the Comanchean of Texas by Hill, numerous fossils, most of them footprints, have since

[4] F. W. Cragin: Vertebrata from the Neocomian of Kansas. Colorado College Studies, Fifth Ann. Publication, 1894, pp. 69-73.

[5] S. W. Williston: On various vertebrate remains from the lowermost Cretaceous of Kansas. Kansas Univ. Quarterly, vol. 3, no. 1, July, 1894.

[6] S. W. Williston: A new plesiosaur from the Kansas Comanche-Cretaceous. Kansas Univ. Quarterly, vol. 6, ser. A, January, 1897.

[7] Pierce Larkin: The occurrence of a sauropod dinosaur in the Trinity Cretaceous of Oklahoma. Jour. Geology, vol. 28, no. 1, January-February, 1910, pp. 93-98.

been found from time to time in that State. All of these footprints were in the Glen Rose limestone, which is considered the equivalent of the upper Trinity. In 1917 Shuler[8] described dinosaur tracks in the Glen Rose limestone near Glen Rose, Texas. He found eight tracks, each measuring 10 by 16 inches. The stride was four feet 2 inches. He believes that these tracks were made by a land reptile at a place where it had walked on mud which was probably covered by shallow water. Shuler proposed the name *Eubrontes* (?) *tilanopelopatidus* for these Comanchean dinosaurs. One of these tracks is now in the geological musuem at Texas Christian University at Fort Worth, Texas.

Under date of December 3, 1928, Dr. Gayle Scott, of this institution, wrote me as follows:

When I first observed the tracks at Glen Rose there were, I believe, four of them, but there were more or less accordingly as the gravel to one side advanced or receded over the rock floor of the creek. So far as I know, the tracks at Glen Rose are all in a straight line and made by a single animal. As they were continually subject to stream erosion, they wore quite rapidly. I have not been there in several years, but I doubt if one could now see much without shoveling a quantity of gravel. The best exposed tracks have been removed. One went to Texas A. and M., one to Southern Methodist University at Dallas, and one came here.

In 1922 Wrather[9] described numerous dinosaur tracks in limestone in the bed of Cottonwood Creek, in southern Hamilton County, in an area 4 to 12 feet wide. At the time of his visit most of these tracks were covered with sand and gravel and he saw only a few of them. He states that reliable persons who have seen the place when it was swept clean by flood waters report that the limestone is covered with a maze of tracks, probably more than a hundred in all.

Both Shuler and Wrather conclude that the tracks "seem to have been made in soft or plastic ooze, which was probably covered by several feet of water."

Most recent Discovery in Texas

The reptilian remains last discovered in the Comanchean of Texas consist of a series of tracks in northeast Kinney County, some 35 miles northwest of Uvalde. The tracks are in the Glen Rose formation, the same that bears the tracks described by Shuler and Wrather. This

[8] Ellis W. Shuler: Dinosaur tracks in the Glen Rose limestone near Glen Rose, Texas. Amer. Jour. Sci., vol. 44, October, 1917, pp. 294-98.

[9] W. E. Wrather: Dinosaur tracks in Hamilton County, Texas. Jour. Geol., vol. 30, no. 5, July-August, 1922, pp. 354-360.

formation is usually regarded as the approximate equivalent of the Trinity of northern Texas and southern Oklahoma.

Mr. C. M. Lawrence, a civil engineer of Holdenville, Oklahoma, who furnished the data regarding the location of the tracks, writes:[10]

> The locus of the fossil tracks is in northeastern Kinney County, nine and one-fourth miles south of the north line, one and one-tenth miles west of the east line, about 200 feet north of a point about 450 feet west of the mid-point, in the south line of survey number 19 (heirs of John Moreland—1157), now part of Paul Edwards' ranch.

The tracks were discovered some years ago by Mr. G. R. Herndon, a ranchman, who showed them to Mr. Pierce Larkin, now a petroleum geologist of Tulsa, Oklahoma. Mr. Larkin very kindly invited me to examine the tracks, and in company with Mr. Lawrence we visited the locality on November 18 and 19, 1928, and obtained photographs and plaster casts of them.

The tracks are found in a ledge of soft gray limestone about half a mile above the mouth of an unnamed arroyo that flows eastward into Liveoak Creek, a tributary of West Nueces River. South of the arroyo there is a hill, several hundred feet high, made up, in ascending order, of the Glen Rose, Comanche Peak, and Edwards formations. These formations consist of soft gray to white limestone and light-colored shale. The bed of the arroyo at this place is 15 to 25 feet wide and consists of soft limestone of the Glen Rose formation. The tracks occur in this limestone.

There are in all about 15 tracks, which are arranged in three groups. Group number 1, the largest, consists of six tracks in almost perfect alignment, three of the left foot and three of the right foot. The average length of the six tracks in the main group is 21 inches; the width is 14 inches. The average depth of the print in the soft limestone is 3 inches. The length of the stride is invariably 5 feet 3 inches. The total distance covered by the six tracks is 28 feet.

Of the six tracks, four were easily seen. Track number 1, however, is very obscure, because the surface of the limestone has been greatly eroded. Track number 2 is shallow, not more than 1½ inches deep. Tracks numbers 3, 4, and 5 are 3½ inches deep and are very distinct. Track number 6 was covered by a higher ledge of limestone, 18 inches thick, but by careful work with the pick we were able to remove the limestone and excavate the soft material that filled the track.

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[10] Personal communication, November 27, 1929.

Photographs of these tracks and a tracing showing their actual sizes were sent to Prof. Richard S. Lull, of Peabody Museum, Yale University. Under date of December 17, 1928, Prof. Malcolm R. Thorpe, of this institution, wrote me as follows:

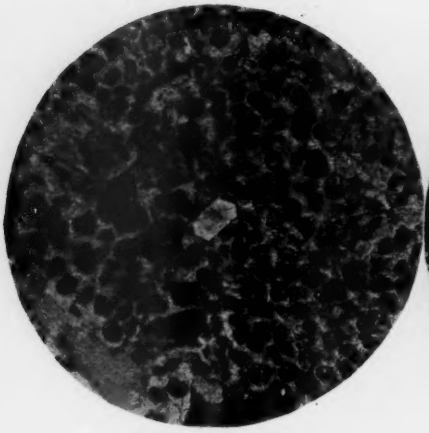
> Doctor Lull has consulted with me in regard to the tracks referred to in your letter of November 24, and illustrated by photographs and tracings, and we are in agreement on the following opinion:
>
> There is a possibility that the Texas tracks might have been made by *Ceratosaurus*, but the footprint of *Ceratosaurus* is somewhat smaller, not being over 19 inches, and the animal himself 17 feet 6 inches. Therefore it seems to us that the animal which made the Texas tracks was larger and heavier. In fact, on the basis of the footprint and total length of Allosaurus, we figure that your specimen must have been about 25 feet long. Furthermore, *Ceratosaurus* has relatively longer claws than Allosaurus, but your print does not clearly indicate large claws.
>
> In our judgment, a more likely possibility is one of the Camptosauridæ, which range in length from 20 feet to 30 feet. The probable length of your animal, size of foot, and the small claw marks, as well as the geologic age (basal Comanchean), are all in favor of this. Without limiting it to one species, either a large *C. dispar* (about 21 feet) or a small *C. amplus* (upwards of 20 feet) might have made the track. However, in the absence of prints of the manus, we can not be positive.

A second group of four tracks occurs in the next ledge above, which is 18 inches thick, at a point about 50 feet upstream from the first group. These tracks are irregularly spaced and are not so perfectly preserved as those of the first group. The largest of these tracks measures 16 by 21 inches. A third group of tracks was found in a small side arroyo, 75 feet downstream from the first group. The largest of these tracks measures 14 by 21 inches. There are three other impressions of single toes, but no impression of a complete foot. There are doubtless many other tracks in this locality, but they can not be seen because they are covered with gravel or solid rock.

My attention has recently been called to two other localities in Texas at which there are said to be tracks of Comanchean reptiles. Both are in the Glen Rose limestone. One is in the bed of Sabinal River a few miles south of Utopia, northeastern Uvalde County; the other is near Bandera, in Bandera County, about 40 miles northwest of San Antonio. Reptilian tracks probably occur at many other places in Texas, and it is hoped that geologists working in that State will examine them and record their location.

Conclusion

The reptilian remains so far found in the Comanchean of Kansas, Oklahoma, and Texas consist of dinosaur bones in the Trinity of Oklahoma and Texas, dinosaur tracks in the Glen Rose of Texas, and plesiosaur and turtle bones in the Kiowa shales of Kansas.



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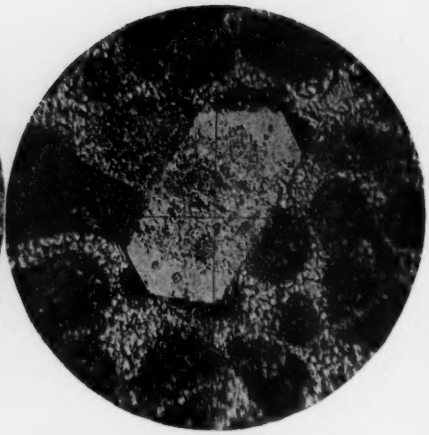

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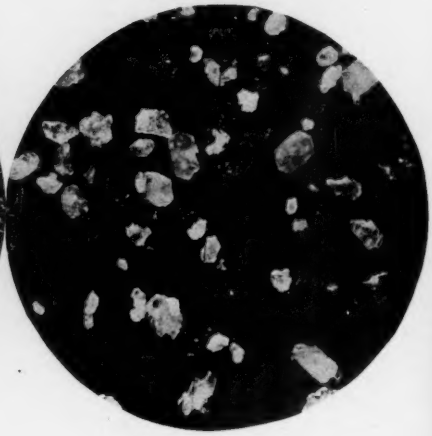

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MICROGRAPHS OF GLENS FALLS LIMESTONE

FIGURE 1.—*Glens Falls Limestone*

Showing characteristic texture and a crystal of authigenic feldspar. Magnification 40.

FIGURE 2.—*Glens Falls Limestone*

Showing characteristic texture and an idiomorphic crystal of authigenic feldspar. Magnification 175.

FIGURE 3.—*Twinned crystal of authigenic feldspar in Glens Falls Limestone*
Crossed nicols. Magnification 200.

FIGURE 4.—*Authigenic feldspars in insoluble residue of Glens Falls limestone*
Magnification 40.

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AUTHIGENIC FELDSPAR IN LIMESTONE AT GLENS FALLS, NEW YORK[1]

BY JOSEPH T. SINGEWALD, JR., AND CHARLES MILTON

(*Read before the Society December 27, 1928*)

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INTRODUCTION

Small quarries on both sides of the Hudson at Glens Falls, New York, are producing stone for lime-burning from beds of Trenton limestone that are 15 feet thick and that dip gently to the south. The lime enjoys an almost exclusive market for use in drawing steel wire because of its freedom from constituents that scratch the wire. A microscopic examination of the insoluble residue of a sample of the limestone showed that it contains many completely developed crystals of albitic feldspar of authigenic origin.

CHARACTER OF THE LIMESTONE

The limestone is a dark gray to nearly black crystalline-looking rock, which in thin-section is seen to consist of clouded aggregates of very finely crystalline calcite in a matrix of more coarsely crystalline calcite. The clouded aggregates are more or less spherical and have a microcrystalline and cryptocrystalline texture. Their dark color is due to an abund-

[1] Manuscript received by the Secretary of the Society January 10, 1929.

ance of minute inclusions of carbonaceous matter. Few of them are over 0.5 millimeter in diameter and most of them are under 0.2 millimeter. The crystalline matrix contains some crystals of calcite having a longest dimension of as much as 0.8 millimeter, but most of the crystals are less than 0.1 millimeter long. The crystals are clear and are apparently free carbonaceous inclusions.

Crystals of feldspar are irregularly distributed through the limestone in the spherulitic aggregates and in the matrix. Many of them show well-defined outlines and twinning. Few of them are more than 0.2 millimeter in length, and most of them are less than 0.05 millimeter. Grains as small as 0.025 are well crystallized and show twinning clearly. Though many of the crystals have idiomorphic boundaries, others have irregular boundaries against the grains of calcite which penetrate them. Chemically the rock is a low silica, low magnesium limestone.

The insoluble Residue

Four hundred grams of the rock were dissolved in cold dilute hydrochloric acid. The effervescence was accompanied by the odor of hydrogen sulphide. The residue contained abundant carbonaceous matter, most of it very finely divided. It was washed to get rid of the carbonaceous matter and was then boiled in nitric acid to remove iron sulphide, which constituted about 5 per cent of the washed residue.

A bromoform separation of the residue showed that the heavy minerals constituted less than 2 per cent of it. The most abundant heavy minerals are garnet, rutile, and zircon. A few grains of tourmaline, titanite, staurolite, hornblende, hypersthene, and barite were recognized.

The float portion of the bromoform separation amounted to 0.7 gram and consisted almost entirely of feldspar in single grains and aggregates and of angular and rounded grains of quartz. Mixed with this portion was still some of the carbonaceous material, which, through the action of the acid and as a result of the heating of the residue in drying, was in the form of cokelike particles.

The Feldspar

The usual forms of feldspar are crystallographically well developed. The crystals show basal and side pinacoids, pyramids, and prisms and have the common habit of feldspar, being prismatic along the *a* axis. The minimum index of refraction is 1.524 and the maximum 1.531, the indices of albite. The optical character is positive. The extinctions on the basal plane are less than 4 degrees; those on the side pinacoid are less than 20 degrees. Twinning is prominent according to the albite, Carlsbad,

and other laws. Cleavage is parallel to the brachypinacoid. Parallel growths are common. The optical properties indicate that the feldspar is albite.

A chemical analysis of the float portion of the separation, generously made by Penniman & Brown, of Baltimore, shows the following composition:

	Per cent
Carbon	0.27
Silica	87.80
Alumina	7.29
Ferric oxide	.09
Lime	1.08
Magnesia	.22
Potash	.19
Soda	3.21

The analysis indicates a content of 35 per cent of plagioclase feldspar, consisting of 80 per cent albite and 20 per cent anorthite, the composition of albiclase. The feldspar crystals may contain enough calcite to account for much of the lime and to explain why the calculated composition of the feldspar is that of albiclase, although its optical properties are nearly those of albite. There is an excess of 65 per cent of silica in the analysis, which represents the percentage of quartz in the residue.

Authigenic Feldspar in Limestone elsewhere

Occurrences reported

Authigenic feldspar has been found in unmetamorphosed limestone at several places in Europe, chiefly in France and Switzerland; at one place in Bengal, and at one place in Canada. Its discovery at Glens Falls seems to be the first one made in the United States.[2] The occurrence in Bengal is described by Edmonson Spencer,[3] who furnishes a bibliography of thirty-five papers on the subject. The occurrence in Canada is described by Daly,[4] who gives a brief review of the European literature on the subject. The fullest description of the authigenic feldspar in limestone is

[2] G. F. Loughlin, in Bulletin 28 of the North Carolina Geological Survey (1921), describes the occurrence of authigenic feldspar in the Cambrian Shady limestone, but the rock has undergone orogenic deformation. A. P. Honess says that he has found authigenic feldspar in the Ordovician Black River limestone. The attention of the authors was called to these two occurrences when this paper was presented to the meeting of the Society in December.

[3] Edmonson Spencer: Albite and other authigenic minerals in limestone from Bengal. The Mineralogical Magazine, vol. 20, 1925, pp. 365-381.

[4] R. A. Daly: Low temperature formation of alkaline feldspars in limestone. Nat. Acad. Sci. Proc., vol. 3, 1917, pp. 659-665.

that given by Grandjean.[5] Other descriptions of occurrences date back to 1861.

CHARACTERISTICS OF THE OCCURRENCES

The occurrences in Canada and Bengal differ from all the others in the abundance of the feldspar. The rock at Waterton Lake, Alberta, contains 40 per cent of feldspar. The limestone in Bengal contains zones of feldspathic rock in which the grains of feldspar are so crowded as to leave crystal skeletons when the calcium carbonate is dissolved. Except in these two occurrences, feldspar appears to be only a minor constituent of limestone. Grandjean gives the amount in two samples as about 0.01 per cent. The sample from Glens Falls contained about 0.05 per cent.

The limestone in Bengal is anomalous also with respect to the size of the crystals of feldspar. Spencer says that the best developed crystals are 1 to 2 millimeters long, and that some are as much as 1 centimeter long. Equally long crystals, according to Foullon,[6] are found in limestone from the island of Rhodes. The usual size elsewhere appears to range from 0.01 millimeter to 0.08 millimeter. The crystals in the limestone at Glens Falls fall within these limits.

The feldspar has been described as orthoclase, microcline, and albite. Grandjean give two analyses and Daly one analysis showing a considerable excess of potash over soda. Spencer gives one analysis showing almost pure albite. The specimen from Glens Falls contains six times as much lime as potash and three times as much soda as lime, indicating an albiclase, but the optical properties indicate albite.

Most of the authigenic feldspar found in limestone occurs in rocks of Triassaic to Eocene age. Grandjean describes an occurrence in Carboniferous limestone near Moscow. The authigenic feldspar found in the limestone in Bengal occurs in rocks of Algonkian or Paleozoic age, and that found in Canada occurs in the Algonkian Belt series. The occurrence at Glens Falls adds another Paleozoic locality.

Mode of Formation of authigenic Feldspar in Limestone

Feldspar is usually regarded as a mineral that is formed at a high temperature, or at least as a hydrothermal mineral. The lowest temperature at which feldspar has been formed hydrochemically in the laboratory is 300 degrees centigrade. As adularia, it occurs in epithermal deposits

[5] F. Grandjean: Le feldspath néogène des terrains sédimentaires non métamorphiques. Bull. Soc. Française de Minéralogie, vols. 32, 33, 1909, 1910, pages 103-132, 92-97.

[6] H. B. Foullon: Über Gesteine und Minerale von der Insl Rhodus. Sitzungber. Akad. Wiss. Wien. Math-Naturw. Cl. 1891, vol. 100, abt. 1, pp. 144-176.

that are believed to have been formed at temperatures between 50 and 200 degrees centigrade. Its occurence as an authigenic mineral in unmetamorphosed limestone suggests its formation at a low temperature. As a result of Grandjean's observations, Doelter concedes that it may be formed at a temperature of 100 degrees centigrade. Daly suggests that it may be formed at temperatures ever lower than 70 degrees centigrade.

The physical conditions under which the feldspar is formed must depend on the time of its formation. The tendency has been to regard its formation as contemporaneous with that of the limestone—that is as contemporaneous with the deposition or consolidation of the calcareous mud, prior to its exposure to a high temperature. This view would bring the temperature at which it was formed well within the lowest limit suggested by Daly, but it does not exclude the possibility that it may have been formed later in the history of the host rock. The Bengal limestone has undergone metamorphism and close folding, and the evidence adduced by Spencer does not preclude the formation of the feldspar at an early stage of this metamorphism. The limestone at Waterton Lake has been buried under more than 6,000 meters of sediments—a thickness that, according to Daly's thermal gradient, would cause a rise in temperature of at least 180 degrees centigrade above that at the surface. However, the limestone in the Paris Basin was never deeply buried and was not subjected to earth temperatures as high as 100 degrees centigrade. The Glens Falls limestone was probably never buried to a depth of 1,000 meters.

The limestone in which authigenic feldspar is found seem to represent chemical precipitates containing organic matter and iron sulphide. It may be that temperatures higher than normal were attained in these calcareous muds through the heat attending chemical decomposition. The peculiar clouded aggregates of the Glens Falls limestone suggest that the calcareous mud from which it was derived may have been heavily charged with particles of organic matter.

Summary

Authigenic albitic feldspar is a constituent of the insoluble residue of a limestone of Trenton age at Glens Falls, New York. The peculiar texture of the limestone and the abundant carbonaceous matter it contains suggest that the rock was derived from a chemical precipitate of calcium carbonate containing many particles of organic matter. The unmetamorphosed condition and the structurally undisturbed attitude of the rock, as well as the probable maximum depth of its burial, indicate

that its temperature has never greatly exceed surface earth temperatures. Chemical decomposition may have caused a moderate rise in temperature.

A survey of the literature shows that authigenic feldspar is not an uncommon constituent of unmetamorphosed limestone. If more attention is paid to the light constituents of the insoluble residue of limestone, it may be found that the occurrence of authigenic feldspar in limestone is rather widespread.

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INTERGLACIAL DEPOSIT IN CENTRAL NEW YORK[1]

BY O. D. VON ENGELN

(*Read before the Society December 29, 1928*)

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INTRODUTION

Although deposits that indicate two or more advances of Pleistocene continental glaciers across New York State have been found at Toronto, Ontario, and in northern New Jersey and southeastern New York, there is no record of the discovery of similar deposits in central New York that are conclusive evidence of the existence of an interglacial period between an inferred early ice invasion and the formation of the deposits assigned to the Wisconsin stage. Several observers have described occurrences that are interpreted as evidence of multiple glaciation, but these occurrences appear to be inadequate to afford a solution of the problem, or the record of them involves misapprehensions as to the nature of the material considered. Although the deposit to be described below is interpreted as evidence of multiple glaciation, the interpretation would be greatly strengthened if other deposits should be discovered that appear to be of the same nature and significance.

EARLIER DISCOVERIES

Maury[2] describes a fresh-water fauna recovered from a high-level deltaic deposit on the west side of Cayuga Lake at a site originally noted by R. S. Tarr. It consists of eighteen identified species, all of which are now living in Cayuga Lake. Eleven of these species have

[1] Manuscript received by the Secretary of the Society December 29, 1928.

[2] C. J. Maury: An interglacial fauna found in Cayuga Valley and its relation to the Pleistocene of Toronto. Jour. Geology, vol. 16, 1908, pp. 565-567.

been found in the warm climate Don Valley beds of the Toronto formation. The stratigraphic succession is: Devonian shale; boulder clay, passing into oxidized sand and gravel at the top, 10 to 15 feet; fossiliferous clay, 5 to 8 feet; gravel and sand, 2 to 3 inches; drift, 20 to 30 feet. It is pointed out that the altitude of the Toronto fossiliferous bed and of the Cayuga fossiliferous bed above the existing water level is the same, namely, 20 feet.

In view of these observations, it is argued that the Cayuga Valley fauna is interglacial; but the identity of a number of its species, all now living in adjacent waters, with the fossil remains in the Toronto bed can hardly be said to establish an interglacial origin for the Cayuga material.[3]

The correlation of levels does not appear to be significant, for Lake Ontario now stands 246 feet and Lake Cayuga 384 feet above sealevel. Further doubt is raised by the fact that the site is described as a ravine cut in a "delta terrace," which suggests that the undescribed upper "drift" may be ill-assorted or slumped deltaic material. On a visit to the site recently no difficulty was experienced in locating the fossiliferous layer. Where seen in two exposures, the overlying material was clearly of deltaic origin. This fossilifemrous bed is undoubtedly a deposit made after the melting of the last ice from the site.

Carney[4] argues at length that the compact, indurated, blue till found under relatively loose weathered material at many places around Keuka Lake is the deposit of an earlier ice invasion. Such blue till, however, is found on the bedrock almost everywhere in this part of the State. Carney recognizes its occurrence in filled valleys that are generally regarded as the product of stream erosion during the time preceding the last ice advance.

The present author is convinced that this compact blue till is subglacially transported boulder clay of the last ice advance. Thus it would very naturally be found in interglacial gorges. On this compacted till

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[3] A. P. Coleman: Glacial and postglacial lakes in Ontario. University of Toronto Studies, Biological Series, No. 21, Toronto, 1922, p. 61: "A comparison of the fauna of the glacial lakes, so far as known, with that of our present lakes, which have no permanent ice on their shores, shows little difference between them. Practically all of the species still live in our waters."

[4] F. Carney: Pre-Wisconsin drift in the Finger Lake region of New York. Jour. Geology, vol. 15, 1907, pp. 571-585.

Idem: The metamorphism of glacial deposits. Jour. Geology, vol. 17, 1909, p. 486: "Glacial deposits, regardless of their constituency, when buried for a long time, appear to become compact and bluish in color." Page 487: "I believe that, so far as the regions considered in this paper are concerned, two Pleistocene epochs are indicated by a contact of the bluish and yellow till."

loose weathered englacial and superglacial drift, appropriately termed ablation moraine, was laid down. The marked distinctness of separation possible and the vast scale on which such superposition could take place was impressed on the present author by observation of the conditions present along the border of the Malaspina Glacier in 1906 and 1909.

In places these distinctive morainic materials are separated by a sheet of water-assorted material, a deposit made by streams flowing under the thin frontal margin of the waning ice. Such ideal threefold division of the drift deposits of a single advance of the ice is not sufficiently appreciated in this country, but is made a topic in a textbook by W. B. Wright,[5] a British glacialist.

Moreover, the compact indurated till in numerous occurrences is present as a thick core in morainic ridges of the Wisconsin stage, specifically in those at Varna, New York. At such sites the till has the characteristic blue tint throughout, but is commonly less compacted in the upper part of a section—a difference which results from the fact that the upper levels of the morainic deposits were subjected to less pressure by the ice.

F. C. Baker [6] reviews Maury's correlation approvingly and calls attention to a reference made by Tarr [7] to the finding of the leaf of an Artic willow, *Salix reticulatus*, in blue clay overlain by 100 feet of morainic material accumulated in an interglacial gorge of the stream in Watkins Glen. Baker thinks this leaf should be correlated with the Scarboro, Toronto, cold climate remains. Tarr is of opinion that it was buried in a deposit laid down at the time of the last advance of the ice, that of the Wisconsin stage. Gilbert [8] describes a plane, formed by glacial erosion, which separates a thick till into slightly different upper and lower parts. He asserts an epoch of till erosion, but recognizes that the evidence is inconclusive, because such erosion may be a part of a stage of readvance that followed a period of local deglaciation.

The intention of the above review is not to find fault with the work of previous observers, but only to point out that the evidence reported, though significant and suggestive, does not certainly establish two stages of glaciation.

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[5] Quaternary ice age. London, 1914, pp. 43-44.

[6] F. C. Baker: Interglacial records in New York. Science, new series, vol. 37, 1913, pp. 523-524.

[7] R. S. Tarr: Watkins-Glen Catatonk Folio, No. 169. U. S. Geol. Survey, 1909, field edition, pp. 192-193.

[8] G. K. Gilbert: Boulder pavement at Wilson, N. Y. Jour. Geology, vol. 6, 1898, pp. 771-775.

Interglacial Gorges

As the evidence afforded by the drift material is inconclusive, the presence of numerous gorges cut into the bedrock and later filled with glacial debris that has been in part removed by modern streams is held to be much more positive proof of two ice advances across central New York. Such gorges are regularly referred to as "interglacial." The fact that they are filled with drift proves that they antedate the last ice advance. Further, streams are now making similar rock cuts. Accordingly, it is argued that the earlier gorges, like the postglacial ones, owe their origin to the diversion of streams from the axes of their valleys to valley slopes due to the unequal thickness of glacial deposits laid

Figure 1.—*Hanging Valley of Sixmile Creek*
Viewed from West Hill, Ithaca, New York. Photographed by O. D. Von Engeln.

down in their channels. This deduction is warranted and can be fortified by other evidence. Nevertheless it is possible that the "interglacial" gorges are the effects of a late Tertiary or early Pleistocene uplift of the region which brought about revival of stream erosion and the consequent rejuvenation of the forms of the valleys.

As the recorded evidence that the central New York region was the scene of two or more ice advances or of a stage of deglaciation properly termed interglacial is not fully convincing, further discoveries of deposits tending to show multiple glaciation of the region have a confirma-

tory significance which is noteworthy. The discovery of such a deposit on Sixmile Creek is here reported.

Topography of Sixmile Creek Valley

The valley of Sixmile Creek extends southeastward from Ithaca, New York, and is a hanging tributary to the valley of Cayuga Lake (figure 1). At least five distinct slopes and rock declivities may be recognized in a cross-section of Sixmile Valley. The uppermost slopes on both sides of the valley are gentle and are regarded as remnants of the preglacial valley, perhaps slightly modified by glacial erosion. Below these there is a steep-sided trough. This trough has the characteristic "U"-form

FIGURE 2.—*Profile of the Bottom of the secondary glacial Trough*

It is intersected here by the postglacial gorge below the pumping station. Ground moraine till rests on the bedrock of the floor of the trough, as shown on the left of the picture. Its presence indicates active scour by the ice of the latest advance at this site. See figure 3 for further explanation. Photograph by O. D. Von Engeln.

ascribed to glacial erosion, and on inspection from a distance it appears to have a flat rock floor (figure 1); but so much of this floor is buried in drift that its continuity across any one line of cross-section can not be proved. Into the bottom of the upper U-trough a similar, shallower, secondary trough has been excavated. This secondary trough is shown in figures 2 and 3.

Ground moraine till rests on the bedrock of the floor of the trough, seen on the left. Its presence indicates active scour by the ice of the latest advance at this site (see figure 3 for further explanation).

It is interpreted by Rich and Filmer [9] as the oldest of a series of interglacial gorges. The rock slope, rather anomalous for a stream-cut, is described by these authors as a surface due to long interglacial weathering that was smoothed out by the scour of the ice of a succeeding advance of the glacier. It would appear much simpler to consider this gorge the result of a second ice advance of less erosive competence than the one which made the larger U-cut. Into the floor of the shallower U-trough there has been cut by stream erosion the 200-foot gorge of Rich and Filmer, held to be of interglacial origin. Throughout a considerable part of its length this interglacial gorge has been cleared of glacial fill by the modern stream, but in its upper stretches the gorge is completely buried by glacial deposits and its course cuts across the channel of the modern stream on the line indicated in figure 2. The fact of such intersection could not be observed by Rich and Filmer, for when they made their studies the top of the rock wall of the interglacial gorge at the site of the intersection was under the water of a filled reservoir. Finally a postglacial gorge starts from the glacially filled part of the 200-foot gorge at this point of intersection and curves around to enter its lower cleared portion about 1,000 feet downstream. Further details of the topographic conditions at the site are given by Rich and Filmer.

While the ice-sheets which extended across central New York were advancing and melting back, the valley of Sixmile Creek, in common with other valleys in this region that drained toward the north, was the site of a proglacial [10] lake. An extensive literature gives the history of the successive levels of these lakes at the time the last ice retreated. This history can be deciphered from deltaic deposits, strand-lines, and outlet channels. But similar features showing drainage ponded in lakes on the advance of the last ice and during any or all previous advances were either swept away by ice scour during the latest glaciation or were greatly modified in form; and deposits were so much commingled with other material as to make their identification rather doubtful. Such, also,

[9] J. L. Rich and E. A. Filmer: Interglacial gorges of Sixmile Creek at Ithaca, New York. Jour. Geology, vol. 23, 1915, pp. 59-80.

[10] Proglacial, "in front of the ice," is suggested as preferable here to "postglacial," which properly refers only to lakes formed during the retreat of the last glacier, and might mean existing lakes. The term "glacial lakes" is also inappropriate, because it is even more broadly inclusive.

FIGURE 3.—*The various Slopes and Declivities of a cross-section Profile of Sixmile Valley*

The locality is the site described.

was evidently the fate of all the morainic deposits made during earlier glaciations.

However, at the site described in this paper, a particular combination of conditions permitted the preservation of a remnant of a deposit laid down during the latest glacial *advance*. The conditions of the occurrence and the nature of the material clearly indicate that the deposit is of interglacial origin.

Description of the Deposit

On the northeast side of the reservoir used in connection with a pumping station for the Ithaca water system a stream has cut a steep rock

FIGURE 4.—*Clifton Gorge of Little Miami River, Ohio*

The fluting formed by stream currents in massive rock is here well shown. The material is limestone. Photograph by O. D. Von Engeln.

wall through beds of durable, fine-grained, massive sandstone. This wall is interpreted as a part of the 200-foot interglacial gorge already mentioned. The gorge here takes a turn to the left across the present stream course, transverse to the shallow inner U-trench. The wall therefore faced upstream—that is, it had a lee position in relation to ice advancing from the north. The sandstone ledges apparently marked the site of a waterfall in the gorge, as these beds are far more resistant than the average bedrock in the region; also, their edges are marked through a vertical range of 20 to 30 feet by deep flutings similar to those

formed by the currents of turbulent streams in the walls of gorges now in process of excavation (figure 4). The surface of these flutings shows little or no weathering.

At the time of the last ice advance the water of the ponded northward-flowing drainage rose in level as lower outlets were closed successively. When escape to the valley of Seneca Lake and the Horseheads outlet was cut off, the water level in the Cayuga drainage system rose progressively, and probably rapidly, in Sixmile Valley. As the strand advanced upstream a torrential delta of gravel was steadily accumulated, and the conditions in the gorge site just described were especially favorable to

FIGURE 5.—*Interglacial Gravels*

The lighter material at X is crowded into flutings of sandstone. Fluting of sandstone is discernible on ledge below deposit. It is a rough rock face from quarry operations. Photograph by O. D. Von Engeln.

its rapid accumulation. Coarse gravel was packed into the flutings of the sandstone ledges, and with further rise of the water level was sealed in by finer deposits and then overridden by the ice. Later glacial erosion excavated the inner U-cut, removing the part of the 200-foot gorge wall that stood in its path; but the ice erosion was not deep or broad enough to erase the 200-foot gorge completely. The remnant of the wall described, together with the gravel crowded into the flutings, escaped such erosion. After the ice had melted, the site was buried under morainic

material and postglacial lake deposits. It has since been uncovered by modern stream erosion and by quarrying and it now appears as shown in figure 5.

The material of lighter shade, marked X in figure 5, consists of greatly weathered and iron-stained, stream-rounded gravel. It contains a characteristic assortment of erratic pebbles, fragments of igneous and metamorphic rock derived from areas farther north, together with fragments of local formations. In particular it contains pebbles of red Medina sandstone in all stages of disintegration. The gravel in the postglacial, high-level deltas is uniformly fresh.

Interpretation

The weathered gravel is interpreted as water-transported detritus derived by stream erosion during interglacial time from the deposits of an earlier glaciation and carried to its present site by the interglacial Sixmile stream immediately before the area was covered by the ice of the last advance. The mixture of pebbles in all stages of disintegration in the deposit would naturally be expected because the interglacial stream was obtaining its load from materials that lay at different distances below the interglacial weathered surface. The remarkable freshness of the sandstone flutings shows that no special conditions promoted rapid weathering at their site, and postglacial weathering in general has not advanced far enough to produce gravel of the kind found here. It may be added that, as the 200-foot interglacial gorge is much wider and deeper than the postglacial cut, and as it apparently slopes downward toward the north and was graded to a base level nearly as low or perhaps lower than that of the postglacial gorges now tributary to Lake Cayuga, it may properly be termed interglacial, because the ice must have been melted back sufficiently far to permit the northward escape of the drainage at levels comparable to those now seen.

The interpretation of this deposit here given would be quite conclusively established by the discovery of similar deposits elsewhere near by. Nearly all parts of the interglacial gorges of the region were filled with morainal deposits during the last retreat of the ice. Under such filling, there should be present patches of interglacial gravel, similarly stream transported, resting on the bedrock of the bottom of the gorge. Gravel bars are seen at some places on the bottoms of the postglacial gorges. As the interglacial gorges were opened more broadly during interglacial time than the postglacial gorges, the interglacial gravels are probably more continuous. The cost of the work prohibits directed excavation

in search of such material, but excavations for new buildings or trenches dug for other purposes may provide exposures. Buried interglacial valleys appear to be of widespread occurrence. Those who are interested in glacial problems should examine carefully any sites where such an exposure may possibly be found.[11]

[11] In April, 1929, Mr. E. W. Hard, a graduate student of geology in Cornell University, discovered an exposure of this nature near Bellona, New York. It has not yet been studied carefully.

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NEBRASKAN, KANSAN, AND ILLINOIAN TILLS NEAR WINCHESTER, ILLINOIS[1]

BY ALFRED H. BELL AND MORRIS M. LEIGHTON

(Read before the Society December 29, 1928)

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INTRODUCTION

As exposures of two older tills beneath the Illinoian are rare, the recent finding of such an exposure near Winchester, in western Illinois, is of special interest (see figure 1).

West of the Illinoian drift border, in eastern Iowa and Missouri, there are two drifts older than the Illinoian, each deposited by an ice-sheet coming from the Keewatin field. One of these drift sheets, and perhaps both, extends eastward across the Mississippi River underneath Illinoian drift for a distance which has heretofore not been regarded as very great. A driftless area in Calhoun and southern Pike counties marks the eastern border of the Kansan drift from the Keewatin field and the western border of the Illinoian drift from the Labrador field. North of this driftless area the Kansan drift border runs underneath the Illinoian, and its position from this area northward to the driftless area in Jo Daviess County is unknown. MacClintock reports deposits of pre-Illinoian till at several points to the east and southeast, at least as far as the Indiana line. Those in eastern Illinois were doubtless laid down by Labradorean ice. Leverett reports Kansan drift in Pennsylvania,

[1] Illinois State Geological Survey studies.
Manuscript received by the Secretary of the Society January 25, 1929.

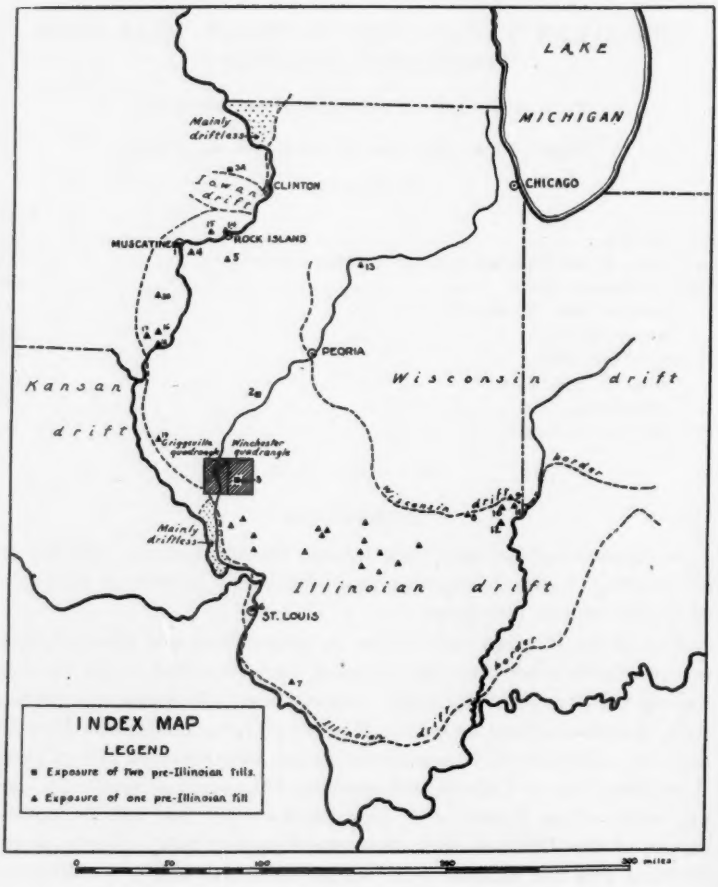


FIGURE 1.—*Exposures of pre-Illinoian Drift in Western Illinois*

and in New Jersey there is the old Jerseyan drift, which may be of Nebraskan age. Both of these were certainly deposited by Labradorean ice.

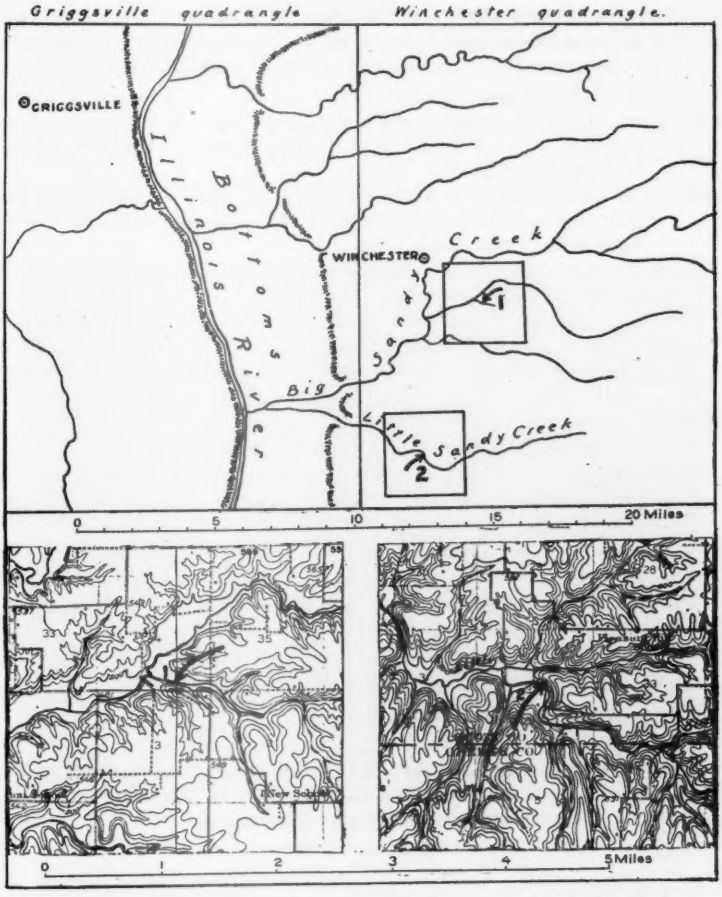


FIGURE 2.—*Location of the Winchester Cut (1) and the Pumping Station Cut (2)*

The question considered here is, To which field do the older tills near Winchester belong? This question is of special interest because of the geographic situation of the tills near Winchester, which lie northeast of the Calhoun County driftless area and east of the Illinois River valley, regarded as the old valley of the Mississippi.

Exposures of pre-Illinoian Drift in Western Illinois

The numbers indicate the sources of the information, as follows:

1. J. A. Udden: Geology of Muscatine County. Iowa Geological Survey, Annual Report, volume 9, 1898, pages 337-339.
2. H. R. Wanless: Nebraskan till in Fulton County, Illinois. Transactions of the Illinois State Academy of Science, volume 21, 1928.
3. The Winchester cut.

3A. M. M. Leighton: Superimposition of Kansan drift on sub-Aftonian drift in eastern Iowa. Proceedings of the Iowa Academy of Science, volume 23, 1916, pages 133-139.

4, 5. T. E. Savage and J. A. Udden: Geology and mineral resources of the Edgington and Milan quadrangles. Illinois State Geological Survey Bulletin 38-C, 1921, pages 52-55.

6. N. M. Fenneman: Physiography of the Saint Louis area. Illinois State Geological Survey Bulletin 12, 1909, page 9.
7. Paul MacClintock: Pre-Illinoian till in southern Illinois. Journal of Geology, volume 34, number 2, 1926, pages 175-180. Reprinted in Illinois State Geological Survey Report Investigations, number 11, 1926, pages 10-15.

8-12. P. MacClintock: Pre-Illinoian drift in Clark County. Transactions of the Illinois State Academy of Science, volume 21, 1928.

13. G. H. Cady: Geology and mineral resources of the Hennepin and La Salle quadrangles. Illinois State Geological Survey Bulletin 37, 1919, page 71.
14. F. Leverett: The Illinois glacial lobe. United States Geological Survey Monograph 38, 1899, page 45.
15. Same reference, page 46.
16. Same reference, page 54.
17. Same reference, page 129.
18. Same reference, pages 52, 56.
19. Same reference, page 59.
20. Same reference, page 42.

The unnumbered exposures of pre-Illinoian till are described by P. MacClintock: Recent discoveries of pre-Illinoian drift in southern Illinois. Illinois State Geological Survey, unpublished manuscripts.

The Winchester Cut

LOCATION AND CHARACTER

The Winchester cut is 2½ miles southeast of Winchester, in the south wall of the valley of a small stream that flows into a tributary of Big Sandy Creek (see figure 2). The cut is 1,600 feet east of the bridge, in the southern part of section 34, township 14 south, range 12 west.

There are no rock outcrops within three-fourths of a mile of the exposure of the drift, the valley walls being composed of unconsolidated material. The cut is 40 feet high at low water and about 100 feet long. The chief stratigraphic boundaries are outlined in figure 3. A detailed section of the formations is given below.

FIGURE 3.—*The Winchester Cut*

The locality is on the south bank of the stream. I, Illinoian; K, Kansan; N. Nebraskan.

Section 2½ Miles Southeast of Winchester, at a Point 1,600 Feet East of Bridge, in Southwest ¼, Section 34, Township 14 North, Range 12 West, Scott County, Illinois

	Thickness, feet
3. Illinoian till: brown in upper part, yellow and gray below; matrix somewhat sandy; upper 5 feet leached, calcareous below; upper 15 feet oxidized	27

	Thickness, feet
2. Kansan till: upper boundary sharp as a knife edge; till clayey, in contrast to the somewhat sandy matrix of the Illinoian; upper 5 to 7 feet oxidized to yellow, lower part dark gray, unoxidized; all calcareous; maximum	11
1. Nebraskan till: 4 feet exposed, 11 feet more penetrated by auger; exposed till greenish brown, much decomposed, very dense, plastic and massive when wet; pebbles few, most of them less than 1 inch in diameter, maximum diameter 1½ inches; mainly chert, fine-grained greenstone, basalt, and quartzite; some coarse-grained granite, pyroxenite, and diabase; till non-calcareous to a depth of 10 feet; calcareous in spots, 2½ feet; uniformly calcareous below	15+

INTERPRETATION

Formation 3 is part of the uppermost drift sheet in the area, the Illinoian. If the underlying oxidized till (formation 2), which is a tight clay, is part of the Illinoian, it is difficult to explain how this till could have been oxidized and the overlying till, which is somewhat sandy, could have remained unaffected, and also why the two tills are separated by a sharp contact. The conclusion seems unavoidable that the oxidized, calcareous till (upper part of formation 2) is part of the weathered zone of an older till, from which an unknown thickness was removed by erosion before the deposition of the overlying Illinoian till. The fact that formation 1 consists wholly of weathered material must be considered in interpreting its origin. The much smaller proportion of pebbles in this material is due to the leaching out of all the limestone and dolomite and the advanced decomposition of part of the igneous rocks. Even if no glacial striæ could be certainly found on the pebbles, the presence of pebbles of igneous and metamorphic rock and the complete lack of bedding leave little room for doubt as to the glacial origin of this material. Inasmuch as two tills older than the Illinoian are found in this cut, they have been referred to the Kansan and Nebraskan glacial epochs.

Source of the Tills

ILLINOIAN AND KANSAN

No striated bedrock surfaces that might indicate the direction of the movement of the ice that deposited any of the tills have yet been found in the Winchester area. It is well established, however, that the Illinoian ice came from the Labrador center. Pebble counts were made from all three tills in the Winchester cut to obtain any possible indication of the direction from which the two older ice-sheets came. Detailed results can not be given here, but the more important features revealed are as follows:

1. The proportion of igneous rocks in the Illinoian till is higher than in the Kansan till.

2. Dolomite is in excess of limestone in the Illinoian till, whereas in the Kansan till limestone greatly preponderates over dolomite.

The differences in the limestone-dolomite ratio and in the igneous rock content of the Illinoian and Kansan tills suggest that the ice-sheets which deposited them came from different directions. The relatively high proportion of dolomite in the Illinoian till is presumably due to the fact that the ice crossed the area of Silurian and Ordovician dolomites in northern Illinois and Wisconsin. It may therefore be suggested that the Kansan till in the Winchester cut came from the west and northwest, inasmuch as the bedrock to the northwest is composed of Mississippian and Devonian limestones. In Fulton County, 45 miles north of Winchester, a similar indication of the Keewatin source of the Kansan glacier, based on the limestone-dolomite ratio determined by pebble counts, is reported by H. R. Wanless (figure 1, number 2).

NEBRASKAN

The pebble count for the Nebraskan till can not be compared directly with those for the Illinoian and Kansan tills because the Nebraskan till is so highly weathered. If limestone and dolomite were once in the till they have been completely leached out, and if originally there was much coarse-grained igneous material it has been largely decomposed. A noteworthy feature of the pebbles now remaining is the high proportion of chert (50 per cent by weight). The proportion of chert in the original Nebraskan till may well have been higher than in the Kansan and Illinoian tills, because the Nebraskan till included residual chert and chert gravels resulting from Tertiary weathering. This might seem to indicate that the Nebraskan glacier came from the west, across the Mississippian rocks, in which chert is much more abundant than in the Pennsylvanian rocks to the east. It should be remembered, however, that although 50 per cent of chert by weight of the present pebbles may seem high, yet the proportion of chert in the pebbles of the original material was much lower. In Fulton County (see figure 1, number 2) Wanless found a higher proportion of chert in the pebbles in the Nebraskan till than in those in the Kansan and Illinoian, even if the limestone and dolomite of the two later tills are excluded from consideration. Neither in the Winchester area nor in Fulton County do the counts of pebbles in the Nebraskan till indicate the direction from which the Nebraskan glacier came.

A suggestion that one of the pre-Illinoian glaciers may have come from Labrador is seen in the westward dip of the cross-bedding in an old buried valley train exposed in a stream cut 6 miles south of the Winchester exposure (pumping station cut, see figure 3).

Changes in Drainage

The successive ice invasions in Pleistocene time have produced great changes in the drainage of the glaciated areas. In order to illustrate some of the changes that have taken place in the Winchester area since the first ice invasion, a generalized contour map of the bedrock surface (figure 4) has been prepared. Although direct information on the elevation of bedrock along the upland divides is scarce, fairly good estimates could be made by observing the elevation of the highest bedrock exposed at the heads of tributary streams. Datum points so determined are shown on the map as solid triangles and most of the contour lines are based on them. The solid circles represent wells or mines that give information as to the elevation of the top of bedrock. The open circles are points in the bottoms of valleys, the elevations of which are shown by figures in brackets. As there are no outcrops of bedrock in the east-central part of the quadrangle, although that part is in places dissected to a depth of as much as 100 feet below the upland divides, the rock surface beneath the divides probably does not stand higher than the bottoms of the present main valleys. How much lower it may lie is not known, and there is not sufficient information to warrant the drawing of contour lines for this part of the area.

The map shows a general westward slope of the rock surface toward the Illinois River valley. Areas of high bedrock lie in the north and south parts of the quadrangle and are separated by a valley trending southwestward. The Winchester cut lies within this old valley, and the presence of Nebraskan till here indicates that the valley was formed prior to the Nebraskan ice invasion. It was doubtless the valley of a small tributary of the preglacial Mississippi, which flowed through the Illinois valley.

If the Kansan till near Winchester was deposited by a glacier coming from the west, as is suggested by the pebble counts, the Mississippi and Illinois valleys were blocked in Kansan time, and slack-water deposits of this time should be found in the extra-glacial portion of the westward-flowing tributaries of the Illinois. Although the Illinois valley is almost certainly of preglacial age, most of the present tributary valleys in this area are so small that they may well be post-Kansan; indeed, some of them are almost certainly post-Illinoian. As slack-water silts

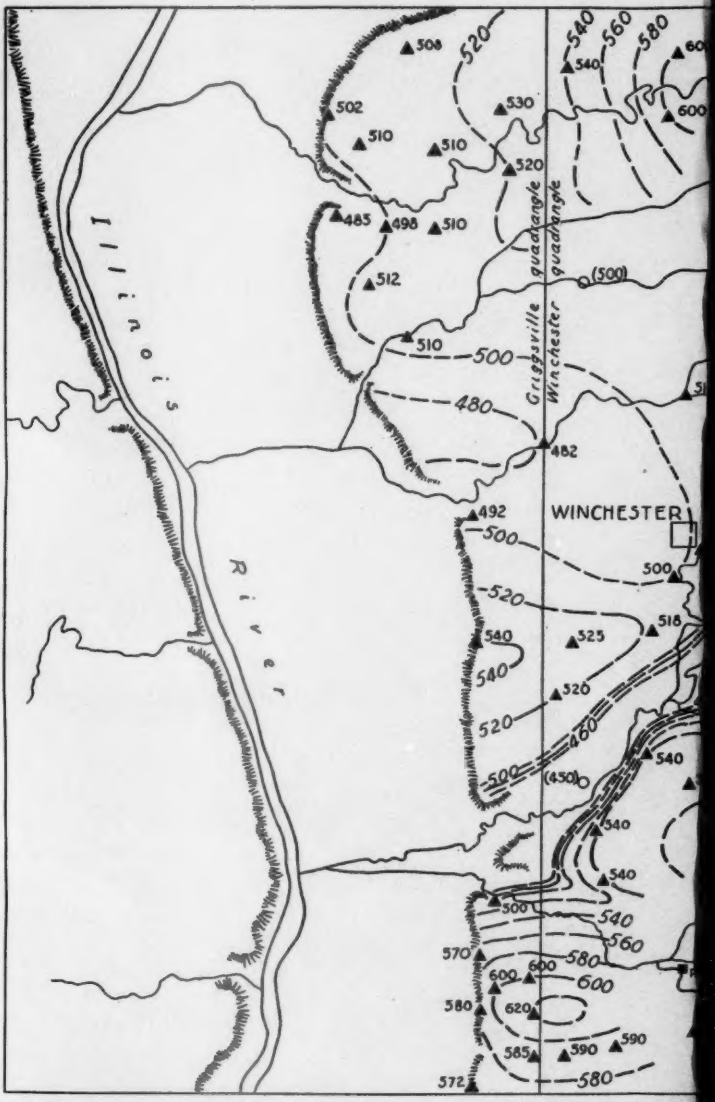
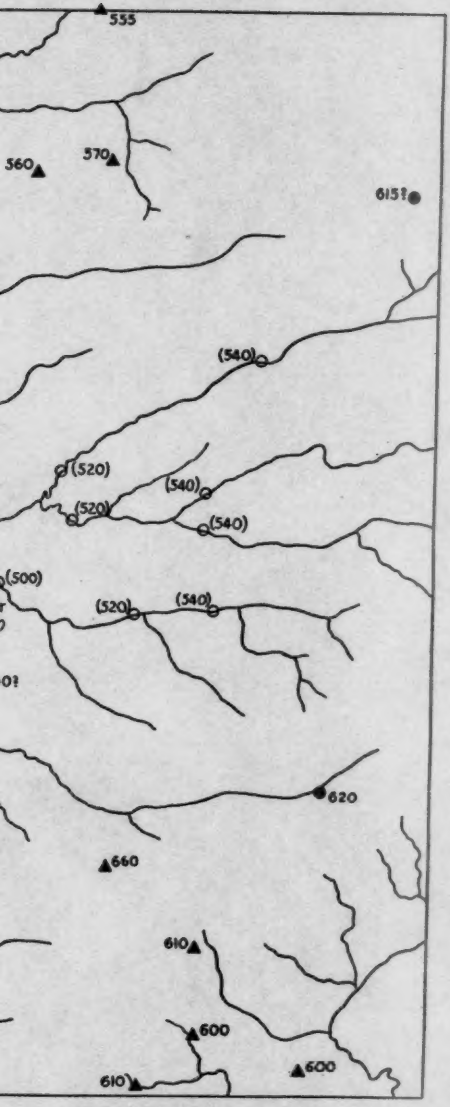


FIGURE 4.—*Contour Map of Bedrock Surface of Part*

(467) Elevation of bottom of auger boring at Winchester cut

drock Surface of Parts of the Winchester and Griggsville Qu



—560— Contour on bedrock surface

Contour interval 20 feet

gsville Quadrangles

of Kansan age were subjected to erosion during the Yarmouth interglacial epoch and as any remnants of them are buried by Illinoian drift, such silts would be exposed only where present drainage lines cross or coincide with pre-Kansan drainage lines. A possible exposure may be seen 2 miles south of Murrayville, near the southeast corner of the Winchester Quadrangle, where contorted slack-water silts lie beneath Illinoian till. In future work evidence of such ponding should be sought.

We have not yet sufficient evidence to make anything like a complete picture of the source and the limits of the early Pleistocene ice invasions in Illinois, but recent discoveries strongly suggest that the Kansan glacier, coming from the Keewatin center, and perhaps also the Nebraskan glacier, advanced farther east than has been thought, possibly as far east as the region about Peoria.

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PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY

ANCIENT MAN IN FLORIDA: FURTHER INVESTIGATIONS[1]

BY JAMES W. GIDLEY

(*Read before the Paleontological Society December 27, 1928*)

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METHODS OF WORK

In the winter of 1927-'28, with the assistance of Mr. C. P. Singleton and two laborers, I excavated large parts of beds numbers 2 and 3 of Sellards, at the locality on the Country Club golf links near Melbourne, Florida. The area worked over is more than 100 feet long and averages 30 feet in width. I also made investigations at Vero, Okeechobee City, and New Smyrna. In this work I adopted, with gratifying results, a method of excavation different from that heretofore employed. Additional evidence indicating the contemporaneity of man with a Pleistocene fauna in Florida was discovered, and facts were thus revealed that necessitate considerable changes in the views formerly held regarding both the origin of the deposits and the distribution and relations of the fauna they contain.

The new method consisted of systematically working over the material in bed number 3 and removing it entirely from the contact plane between the two beds before working bed number 2. In this way areas several square yards in extent of the undisturbed surface of bed number 2 were exposed to view and closely examined. Some significant features

[1] Manuscript received by the Secretary of the Society February 20, 1929.

not before noted of the structure of the beds and of the mode of their accumulation were thus at once revealed, and the observations were fully verified as the work progressed.

Character of the Beds examined

First, it was discovered that bed number 3 is a swamp deposit and that it is almost barren of the remains of vertebrates above its contact with bed number 2, except where it had obviously been disturbed by the action of the stream that traversed the swamp before it had been drained by the recently built canal. The contact plane itself, however, is highly fossiliferous. Broken and scattered bones, jaws, and fragments representing an extensive land fauna, as well as some human artifacts, including bone and shell implements and potsherds, were found at the contact, most of them lying directly on the irregular surface of bed number 2. The fossils were not waterworn and had evidently been deposited where they were found after bed number 2 had been formed and before the deposition of bed number 3 had begun. Nowhere was there found any evidence of later intrusion of material from above, but in the deeper hollows in the surface of bed number 2 material belonging in the contact plane was mixed with other material, including bones of the elephant, mastodon, horse, and other animals, which had evidently been worked out of bed number 2, in which they had originally been deposited. Several of the older bones were in part embedded in the undisturbed, more compact sand of bed number 2 (see figure 1, plate 15). This contact-plane fauna is undoubtedly what has heretofore been considered the fauna of bed number 3.

Another significant fact noted was the peculiar unevenness in the contour of the contact plane. It was found that this unevenness was not caused by stream erosion, as had formerly been supposed, but by relatively small basin-shaped depressions, of unknown origin, of different sizes and depths. The configuration thus formed is strikingly like that of certain areas that may be found today in the so-called prairie country of Florida west of Melbourne, where, during dry seasons, the wet-weather ponds gradually dry up and their shallow, basin-like beds are trampled and wallowed over by the native wild hogs, cattle, alligators, and other animals. This fact suggests a possible origin of the type of surface observed here. Some of the largest of these depressions on the area excavated had a depth of 2 feet or more and a width across the rim of 4 to 6 feet. Their structure and character shows that they had been worked into the surface of bed number 2 when it was more nearly level. The upper part of bed number 2, for a depth of a foot to 18 inches, is

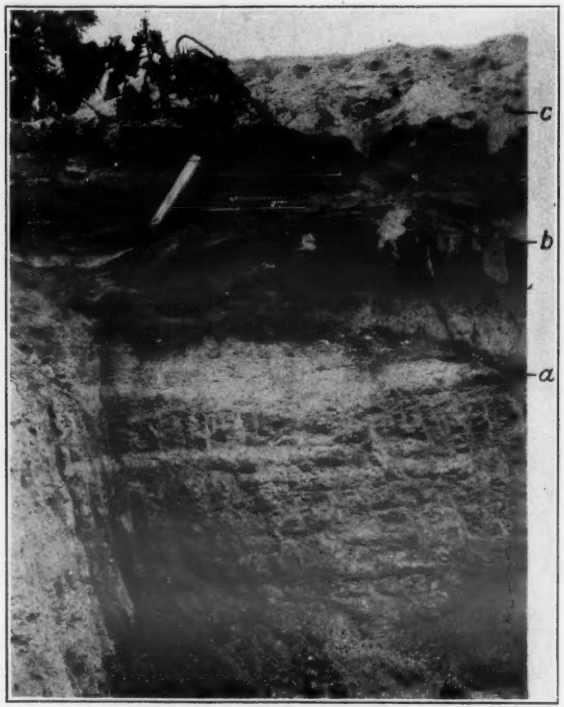

FIGURE 1.—*Section on south Side of Crane Creek Canal, about 2½ Miles West of Melbourne, Florida*

FIGURE 2.—*Same Section as Figure 1, taken about 50 Feet farther West*

CROSS-SECTIONS OF SELLARDS' THREE FORMATIONS

These formations are designated by Sellards as beds numbers 1, 2, and 3. All below *a* is bed number 1; bed number 2 is between *a* and *b;* bed number 3 is between *b* and *c;* above *c* is remnant of spoilbank. In figure 1 the stick at upper left is resting on bed number 2 and lies across bed number 3.

composed of dense, semiconsolidated fine sand, which gradually merges into the coarser, looser sand of the lower part of the bed. A few of these hollows were deeply cut into the more consolidated upper part of bed number 2, occasionally the cut forming a perpendicular or even overhanging bank on one side. This semiconsolidated condition of the upper part of bed number 2 is evident wherever cross-sections of it were observed. This part of the bed, moreover, is marked everywhere by numerous vertical dark streaks, evidently the remnants of old roots of scrub palmetto, which seem to have covered the surface of the completed bed prior to the excavation of the basin-like depressions, before the swamp was formed in which the deposits of bed number 3 were laid down. Similar remnants of grass roots were seen, especially around the borders of some of the larger basin-like depressions. All this denotes a rather long period of time intervening between the completion of deposition of bed number 2 and the beginning of the accumulation of bed number 3. It was during this period that the animal and human remains found at the contact plane were deposited.

These features of the bed must be considered in determining the geological horizon or age of the crushed human skull found by the Amherst-Smithsonian Expedition in 1925. This skull, crushed and flattened, was completely embedded in the more compact, root-marked, and undisturbed upper layer of bed number 2 which at the time of the discovery was not recognized as being so distinctly separated from bed number 3, above. The skull is therefore now known to belong to bed number 2. An arrow point found in the middle of the section worked at Melbourne this year furnishes additional evidence that man lived in Florida at the time bed number 2 was formed, and the finding of a few human bones, three arrow points, and a bone implement in similar undisturbed deposits at New Smyrna must also be considered.

Much has been said about the possibility of mixtures of ancient and modern material in these beds, but the fauna of bed number 2 was everywhere distinctly Pleistocene and no evidence was found that it was mixed with material of a later time. The only evidence of a mixture of faunas, as already intimated, was seen at the contact zone. It therefore seems probable that the remains of the mammoth, mastodon, horse, camel, tapir, and other animals found by earlier expeditions above the contact plane had been worked out of bed number 2 by the agencies—human or animal, or both—that formed the basin-shaped depressions before bed number 3 had been laid down. In certain of the depressions this sort of mixing is evident.

It is equally evident in certain other areas that the present-day channels of the streams in the swamps have churned up and mixed some of the material of both beds and of the contact zone. Such action was especially effective at the locality near Vero, where there was evidently more disturbance of this sort than at the locality near Melbourne.

The contact plane between bed number 1 and bed number 2 was also critically examined, but here the uneven contours appearing in cross-sections were extended in continuous elongate or channel-like depressions and ridges, indicating erosion by streams or currents. On this contact plane also there are areas or lenses of worked-over and redeposited coquina shells which are at some places interstratified with the layers of sand at the base of bed number 2—a further evidence here of erosion by running water.

The conception here outlined of the general character, composition, and structure of the deposits and the contact zones included in beds numbers 2 and 3 of Sellards at Melbourne and Vero requires a revision of the theory of their origin and growth. Both beds lie above sealevel formations, in contrast with bed number 1, the marine bed that underlies them, but the geological history of all three beds is connected, and bed number 1 must therefore be included in the inquiry.

Origin of Bed Number 1

Bed number 1 of Sellards of the deposits at Vero and Melbourne is part of an extensive geologic unit that apparently underlies most of the lower part of the Florida peninsula. To this unit Sellards gave the name Anastasia formation. It is of marine origin, its main mass being made up of quartz sand containing many marine shells and some corals. At many places the shells greatly predominate, forming shell beds which in certain areas have hardened into rock. Some of these shell beds are so little disturbed that they indicate deposition offshore in shallow water. At Vero, Melbourne, and other places along the east coast the Anastasia formation is capped with layers of shells of coquina, most of which are much broken and waterworn, indicating a shoreline a few miles farther inland than the present one.

After the Anastasia deposits had been formed, it appears that the general landmass was raised to a level where its surface was long subject to the action of the tides. Evidence that this period of tidal erosion was long is seen in the generally level or slightly undulating surface of bed number 1 and in the relatively deep channels of the streams that now drain the lowlands of the Florida peninsula—channels that were probably formed at that time. After the upward movement had car-

ried the relatively even surface of the general landmass above sealevel, so that the tides no longer flowed over it, erosion ceased except in the deeper stream channels. Vegetation then began to grow, probably at first along the borders of depressed areas, and to spread over the flat landmasses that had been covered formerly by the sea, and the deposition of bed number 2 began its slow accumulation through the agency of windborne sand. The invasion of land animals probably closely followed the invasion of vegetation.

Origin of Bed Number 2

Bed number 2, as already stated, is made up largely of sand. It shows little stratification and is apparently almost as widely distributed as the Anastasia formation. In typical areas, where overlaid by bed number 3, it averages not more than 4 or 5 feet in thickness and is nearly everywhere similar in character and structure to the beds at Melbourne and Vero. Fragments of bone may be found almost everywhere in it, but they are most abundant in the areas covered by bed number 3—that is, in the more distinctly depressed areas of bed number 2.

In certain open and slightly higher areas, such as the "prairie" country west of Melbourne, bed number 2 is less deeply covered, being overlain by a thin deposit of vegetable mold and sand like that of bed number 2 proper; but there the recent deposits merge imperceptibly into the older deposits, there being between them no sharply marked contact plane, such as that seen in the areas covered by bed number 3, which is confined to areas that conform in general to the shallow and relative long valley-like depressions that were apparently inherited from similar low areas left by tidal action in the surface of bed number 1.

Now the origin of a widespread, nearly level, relatively thin deposit of sand, such as that forming bed number 2, is difficult to explain as due to the action of streams, especially as the landmass on which it was formed lies so near sea level, between two great bodies of water and far from hills or mountains. A study of the present physical conditions in Florida, however, suggests both the source of the material and the agency that carried and distributed it. Hundreds of miles of beach sand flank both coasts of Florida. The waves, especially in heavy storms, and the winds when the surface is dry are constantly piling up sand in dunes along the shores. Obviously the sand of bed number 2 was derived from this source. An ordinary wind blowing over dry, loose sand will pick it up and drive it forward in sheets that flow over the ground like a liquid. The continuous action of the waves and winds for thousands of years and the leveling action of the heavy rains as the sand was

carried from the coast inland have been sufficient to produce every feature of the formation.

The condition and the manner of deposition of the fossil bones found in the deposits confirm this interpretation. Vertebrate remains are found in the deposit at all levels, although they are somewhat more abundant near the base and near the top. Most of the bones are broken and scattered, yet their broken edges are rarely waterworn. Furthermore, the scattered pieces are not mixed promiscuously as they are in a stream deposit, but many examples were noted where bones belonging to a single individual or pieces of a single broken bone had been scattered before covering over several feet of spore, as indicated by the fact that they were found on the same level. They rarely represent more than a small part of the animal, indicating slow covering. Some of the bones that represent a single animal were found partly in the undisturbed bed number 2 and partly mingled with the contact-zone material at the bottom of a large depression. Such distribution and condition of material appears to indicate a slowly accumulating deposit of wind-blown sand on a surface subject to frequent rainfall, but not a surface on which streams were active.

Another evidence of slow accumulation is the fact that very few large or high-arched pieces, such as tortoise shells, skulls, or pelvic bones, were found buried intact. The specimens are all either broken and scattered, with many pieces missing, or are broken and crushed into a more or less flattened mass. Several crushed shells of land tortoises were found in a condition comparable to that of the human skull taken from this bed in 1925. The crushed skull and pelvis of a mastodon were also found last winter.

Animal remains that were slowly disintegrated and scattered may be found today in the so-called prairie areas west of Melbourne, where conditions are now apparently similar to those that must have prevailed during the long period in which bed number 2 was being formed. In fact, the chief difference in the conditions apparently consists in a difference in the assemblage of animals that inhabited the region.

Origin of Bed Number 3

The contact zone evidently represents a period of general but not great emergence, following the formation of bed number 2, when deposition was checked by a rather complete covering of vegetation. Following this period the deposits that formed bed number 3 began to form and have continued to accumulate up to the present time.

Bed number 3 is softer and looser than bed number 2 and is strikingly different in its general composition. It is made up largely of swamp muck and less completely decomposed vegetation, which includes many thin layers of almost pure leaf mold interstratified with layers and lenses of pure quartz sand, which are most abundant in the lower part of the bed. The swamp muck is thickest at the top of the bed, where in places it is a foot or more thick. The layers of leaf mold and other vegetable matter are more or less mixed with sand, but the layers and lenses of sand, especially those near the bottom of the bed, are almost pure, and the dividing line between the sand and the leaf mold are sharply defined. The layers of leaf mold, which were evidently laid down in quiet water, are light and fragile. Even a gentle current of water would disturb them or tear them apart, so it is inconceivable that stream currents could have brought in even the layers of sand found in the bed. Winds, however, which blow for days at a time in Florida, could have brought in even the thick layers of sand found in the bed.

Bed number 3 is restricted to certain areas which are widely scattered and which conform to the valley-like depressions in the surface of bed number 2. These depressions deepen slightly as they approach the coast, as at Crane Creek, in the Melbourne district, and at Van Valkenburg's Creek, in the Vero district. It therefore seems that at this time there was a slight subsidence of the land—not sufficient to permit its overflow by the sea, but just enough to keep the lower areas continuously submerged by rainwater. An invasion of an abundant swamp flora soon produced bed number 3.

The swamp origin of bed number 3 was suggested in a paper presented to the National Academy of Sciences in 1928, but the bearing of the suggestion on the question of the natural association of the material found beneath it seems not to have been generally appreciated, and I therefore now wish to emphasize certain facts in this connection: First, the formation of swamps in these places would drive the land mammals back to higher areas, so that the absence of their remains in bed number 3 is natural. Second, men would scarcely choose such areas as burial places. Third, bed number 3 is of such texture and character that human bones or artifacts could not have passed through it without human aid while it was covered with water.

Ignoring the effect of swamp conditions in excluding the recent intrusion of anything into bed number 3, it may be said that the loosely assembled and sharply stratified layers of the bed have in themselves effectively sealed everything beneath them, forming a seal that could not be broken through and restored in such a way as to conceal the facts

from the trained eye of a collector. The facts thus stated should forever put to rest all suggestions that the remains of man and of human artifacts are of later age and more recently were intruded into the older formations, such as those found at Melbourne and Vero, by human burial, holes made by animals, decayed tree roots, and other agencies, as well as suggestions that cyclonic storms or the wallowing of alligators may have played a part in confusing the beds. In view of the facts here set forth, all these suggestions seem to me untimable, and the burden of proof must now lie with those who insist upon them.

Summary of the Geological History of the Area

My study by new methods of beds numbers 2 and 3 of Sellards, especially at Melbourne, Vero, and other places in Florida, has materially changed the views I expressed in 1926 in a paper prepared by Dr. Loomis [2] and me. The revised conclusions may be briefly summarized as follows:

1. The irregular surface of bed number 1 of Sellards is due to a long period of slow emergence of the landmass of the Florida peninsula, during which large areas along both coasts and for considerable distances inland were subjected to the action of tidal currents.

2. Continuation of this uplift brought the main landmass to a height at which it remained above sealevel. When this stage was reached the erosion of the main mass ceased, except in the deeper depressions left and the channels that had been formed, and the deposition of bed number 2 began simultaneously with the invasion of the emerged areas by vegetation. As this vegetation spread over the land a Pleistocene fauna also began to occupy it and continued to occupy it for a long time. The growth of bed number 2 was evidently slow. This bed was presumably formed by wind-blown sand plus the leveling action of rains on a surface that had a low gradient. This sand was derived from the beaches and dunes along the coast, and under such conditions but a few feet of thickness must represent a long period of accumulation.

3. At the close of the time phase represented by bed number 2 there was a rather radical change in the fauna. There was also a cessation of accumulation at least in areas that had been covered with vegetation. This stage was characterized by a peculiar type of erosion, which marked and scarred the surface of bed number 2 with basin-shaped depressions, apparently made by man or perhaps by animals seeking water in the drying-up basins during drouth seasons.

[2] J. W. Gidley and F. B. Loomis: Fossil man in Florida. Amer. Jour. Sci., vol. 12, 1926, pp. 261-262.

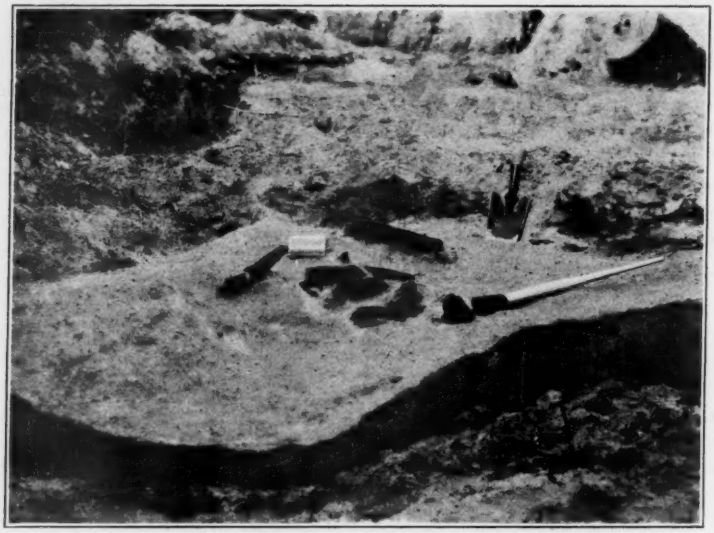

FIGURE 1.—*Cleared Surface of original Top of Bed Number 2*

The view is at the Pleistocene fossil bone locality on Country Club Golf Links, Melbourne, Florida, and shows pieces of mastodon bones still in place, as they had been worked out of bed number 2 before bed number 3 was laid down. More than six inches of the bone protruding at the end of the paint brush was still covered by undisturbed bed number 2.

FIGURE 2.—*Same Locality as Figure 1, about 100 Feet farther South*

One of the largest kettle- or basin-like depressions in bed number 2 surface, after bed number 3 had been carefully removed. This depression was about four feet in diameter and about two feet deep.

VIEWS OF BED NUMBER 2

4. Following this stage, there seems to have been a slight subsidence of the general landmass, which was not sufficient to allow a reinvasion of the sea, but which brought the lower areas so near to sealevel that they were in places covered by land water, and the formation of bed number 3 began. Swamp vegetation next converted these areas into the swamps that have continued to the present day.

Age of Bed Number 2

The age of bed number 2 has been discussed by Sellards, Hay, Loomis, Gidley, and others. All agree that it contains a distinctly Pleistocene fauna. Moreover, the general aspect of this fauna is like that of the first interglacial epoch, the Aftonian, as is noted by Hay, who for this reason has decided that the beds containing it are not later than mid-Pleistocene. In my opinion, however, this determination has not been established, for even if the general assemblage of the genera of the two faunas is similar, a critical comparison of the material seems to show that most of the species are different, especially the horses, camels, and Proboscidians, the principal animals noted by authors as denoting an older phase. The fauna includes several forms that lived in a warm climate and that are not found in typical Aftonian deposits at localities in glaciated areas. Among these are tapirs, a capabara, three or four genera of edentates, an alligator, and several species of land tortoises. In fact, the fauna of bed number 2 as a whole may be considered a southern or subtropical assemblage and may be a late phase of a typical representative fauna that from early Pleistocene time continuously inhabited Mexico and the southwestern United States, and that later worked its way eastward, along the shore of the Gulf, to Florida and was not much disturbed by the recurring advances of the great ice-caps to the north.

The disappearance in northern localities of *Archidiskidon imperator* in mid-Pleistocene, for example, together with the camels, horses, tapirs, and sloths, may thus be explained without postulating their extinction at that time. It would seem to be more reasonable to regard the species found in the north as migrants from this southern fauna. These migrants, having wandered far north of their usual range during relatively long and warm interglacial epochs, may have been driven south again to their more permanent range by later advances of the ice, and they may well have continued to remain there until near the end of Pleistocene time. Thus the first northern invasion would have occurred during Aftonian time, and most of the areas invaded seem to have lain west

of the Mississippi River. This invasion records the only appearance of the imperial mammoth and camel in northern regions.

The next interglacial period witnessed the second invasion, which apparently covered mainly areas east of the Mississippi River. This invasion again included horses. This time they were accompanied by tapirs, ground sloths, peccaries of two types (*Platygonus* and *Mylohyus*), and other forms. The end of this epoch also apparently marked the last appearance of horses in the north, but not necessarily their extinction, for they may have continued on in Southwestern North America, and the imperial elephants and camels casual.

Thus the evidence of the age of the fauna of bed number 2 is not conclusive. The presence in it of *Archidiskidon imperator,* horses, and camels, if interpreted according to the view generally accepted, tends to show that it is early Pleistocene, but it contains also abundant remains of *A. columbi,* which, according to Osborne, is a late Pleistocene species. If, however, the theory outlined above regarding the North American Pleistocene fauna as a whole is accepted, these apparently conflicting bits of evidence would be reconcilable.

Age of Bed Number 3 and of the contact Zone

Whatever may be the final decision as to the exact age of bed number 2, it is evident that a considerable time elapsed between the deposition of bed number 2 and that of bed number 3, and that during that time the fauna changed from a distinctly Pleistocene phase to a more recent phase; but this fauna and the human remains and artifacts found with it are separated from the deposits of historic time by swamp deposits that must represent hundreds and possibly thousands of years. Hence the age of the contact zone seems to lie somewhere between a period definitely Pleistocene and the time phase to which belong the recent mound-building Indians of Columbus and immediately pre-Columbus time.

Bearing of the Facts on the Problem of the Existence of ancient Man in Florida

Many of the facts stated have a direct bearing on the problem of the existence of man in Florida at the time these beds were formed:

1. At Melbourne and at Vero, bed number 3 proper, which was evidently formed in a swamp, contains no remains of vertebrates, and it is not probable that in this bed recent material could be mixed with older material.

2. The character and composition of bed number 3 precludes the possibility that holes or excavations made through it might escape detection. Therefore the human remains and artifacts found near Melbourne, whether from the contact plane or bed number 2, can not be later intrusions, but were originally deposited where they were found. This statement applies also to Sellards' earlier discoveries at Vero.

3. Both the faunal remains and the human artifacts found in the contact zone have a more modern aspect than those in bed number 2 and evidently represent a later phase. Among the artifacts found in this zone are finely worked bone implements and some potsherds. The potsherds, however, include no ornamented pieces, and some of them had not been hardened by firing.

4. No potsherds seem to have been found in bed number 2, and the human skull found in 1925 shows all the characteristics of fossilization that are common to the remains of animals found in that zone, including the dark-brown, semitranslucent coloring of the enamel of the teeth. Both these facts indicate that the human remains found in bed number 2 are older than those found in the contact zone.

5. The fauna of Sellards' bed number 2 is distinctly Pleistocene in aspect and, as regards genera represented, is much like that of the Aftonian stage. For this reason bed number 2 has been considered as old as middle Pleistocene. It is possible, however, that it may belong to a much later stage.

Conclusions

My present conclusions, based on the human remains and the associated faunas found in Florida, are, then, that man reached Florida contemporaneously with a Pleistocene fauna; that he continued to remain there after most of this fauna had disappeared; and that he occupied the country in great numbers before certain changes produced conditions that permitted the formation of the swamp deposits of bed number 3 and probably before the period of the mound-building Indians of the time of Columbus.

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STRUCTURE OF THE METAMORPHIC BELT OF THE CENTRAL APPALACHIANS[1]

BY ANNA I. JONAS

(Presented before the Society December 27, 1928)

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GENERAL FEATURES OF THE STRUCTURE

The folded belt of the Appalachians southwest of New York may be divided into two parts, a belt of unmetamorphosed rocks of the Appalachian Valley and a belt of more or less metamorphosed rocks lying between the southeast side of that valley and the border of the Coastal Plain. The metamorphosed belt consists of two parts, the Highland-Blue Ridge anticlinorium, which is a part of the Appalachian Mountains, and an area of overthrust rocks, the Martic thrust-block, which lies southeast of the anticlinorium and was brought to its present position by thrust-faulting.

The rocks of the metamorphosed belt are closely folded, and are broken by thrust-faults that show all gradations from broken, recumbent anticlines to clean-cut thrusts developed from them. The Martic overthrust

[1] Manuscript received by the Secretary of the Society March 13, 1929.
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is a low-angled thrust of the Scottish Highland type, which has carried the southeastern part of the Appalachians over the Paleozoic limestones that are infolded in the Highland-Blue Ridge anticlinorium.

The entire inner Appalachian belt has been profoundly modified by Triassic normal faulting, which makes the interpretation of the older structures more difficult.

Sections across the Strike

General statement

The structure of the region between northeastern Pennsylvania and northern North Carolina may be best understood from a description of three sections across the strike.

Section across Pennsylvania

The first section is taken across eastern Pennsylvania from the Coastal Plain to Lebanon Valley. In the southeastern part of this region there is a narrow area of the Martic thrust-block, made up of the pre-Cambrian Baltimore gneiss basement and the unconformably overlying thick Glenarm series, composed of pre-Cambrian crystalline schists and intrusive rocks, also pre-Cambrian. This belt of crystalline schists is thrust northwestward over Lower Cambrian slate, quartzite, and limestone and the Ordovician limestone that occupies synclinal valleys in the Highland anticlinorium, such as the Chester, Quarryville, Lancaster, York, and Hanover valleys. This thrust-block has been traced southwestward from eastern Pennsylvania through Maryland and Virginia into North Carolina. The irregular outline of the surface emergence of the fault-plane and the presence of fensters of underlying limestone near its emergence show that the Martic thrust-fault has a low-angled plane that has been folded since the thrusting took place. The surface emergence of this plane transgresses northwestward across the strike of the underlying rocks from eastern Pennsylvania to Maryland, so that folds of the anticlinorium which are uncovered in eastern Pennsylvania are overridden by the thrust-block in southern Pennsylvania. This condition may have been caused by a farther advance of the thrust-block in the southwest or by its more extensive erosion in the northeast. The Coastal Plain sediments cover the southeastern edge of the thrust-block and completely overlap it on the northeast from Trenton, New Jersey, to New York City.

The Highland-Blue Ridge anticlinorium, which lies northwest of the Martic thrust-block, consists of anticlines of igneous and sedimentary pre-Cambrian schists and gneisses and of synclines of Lower Cambrian

and Ordovician quartzites and limestones. The pre-Cambrian rocks occur in several uplifts southeast of the Appalachian Valley, a southeastern belt forming the Mine Ridge Hill-Honeybrook upland east of Susquehanna River and the Hellam and Pigeon Hills southwest of that river, and a northwestern belt forming the Reading Hills and South Mountain, in Lebanon County, east of Susquehanna River, and the Catoctin-South Mountain anticlinorium southwest of that river. East of the Susquehanna a depression in the folding across both these belts exposes Paleozoic limestones and Triassic beds.

Thrust-faults are numerous in the Highland-Blue Ridge anticlinorium and most of them are broken anticlines thrust northwestward over synclines. They are especially numerous in northeastern Pennsylvania and New Jersey, and it is suggested that that area contains also low-angled thrust-faults, but detailed work that might confirm this suggestion has not yet been done there. East of Delaware River, however, the pre-Cambrian rocks of Jenny Jump Mountain have been thrust over the limestone formations of the Appalachian Valley on to the Martinsburg shale that lies north of the valley.

SECTION ACROSS MARYLAND

A section from southeast to northwest in Maryland shows a wider area of the Martic thrust-block. Here, as in Pennsylvania, it contains anticlines having a core of older pre-Cambrian rocks, the Baltimore gneiss and its pre-Glenarm intrusives, which are overlain by younger pre-Cambrian rocks of the Glenarm series. The Martic block contains also the Peach Bottom syncline, which includes infolded slates of unknown age, and the Tucquan anticline, which is the southwestern continuation of the anticline of the Mine Ridge upland. The Mine Ridge Hill anticline, which is a part of the Highland anticlinorium, is covered by the thrust-block southwest of the Mine Ridge uplift and is there called the Tucquan anticline. Pre-Cambrian intrusive rocks occur in the southeastern part of the belt, and surface volcanics of the same age occur in the northwestern part. Lower Cambrian slates and quartzites overlie the pre-Cambrian rocks of the thrust-block in southern Maryland. West of the surface trace of the Martic fault-plane, limestones of the southeastern sequence, characterized by Chazyan limestone,[2] occupy Frederick Valley, which is a syncline that lies along the eastern foot of Catoctin Mountain in Maryland and northern Virginia. These limestones, as well as the rocks of the Martic thrust-block and the Triassic

[2] G. W. Stose and A. I. Jonas: Ordovician shale in southeastern Pennsylvania. Bull. Geol. Soc. Amer., vol. 39, 1927, pp. 524-526.

sediments, have been dropped down on the east side of the Catoctin-Blue Ridge anticlinorium by normal Triassic faults, which extend across Maryland and Virginia into North Carolina.

The anticlinorium in Maryland is composed of one major anticline of pre-Cambrian igneous and sedimentary schists and gneisses and of minor synclines of Lower Cambrian slates and quartzites. The synclines of limestone exposed in Pennsylvania north of Pigeon Hills, in the anticlinorium, are not preserved in Maryland, where the two uplifts exposed in Pennsylvania are combined into one major arch. No syncline of Paleozoic limestone occurs within the anticlinorium from the Mason and Dixon line to central North Carolina, where Lower Cambrian limestone [3] occurs in a narrow syncline south of Linville Falls.

The western border of the Catoctin-Blue Ridge anticlinorium in Maryland is a thrust-fault which lies along the western front of South Mountain and Elk Ridge and extends southwestward across West Virginia and Virginia, along the western front of the anticlinorium. The westerly movement has carried the thrust-block over the rocks of Hagerstown Valley, in Maryland, but on the northeast, in Pennsylvania, where the thrust passes within the anticlinorium, the thrust-block has overridden a western part of the anticlinorium.

SECTION ACROSS VIRGINIA

A section across the strike in central Virginia shows a belt of the Martic thrust-block still wider than that in Maryland. The Peach Bottom syncline, which lies west of the anticlinal axes in Baltimore gneiss, contains Ordovician slates. The western edge of the Martic thrust-block is covered by down-dropped Triassic sedimentary rocks between Potomac and Rapidan rivers, but south of the Rapidan it rests on the Everona limestone of Chazyan age. The Everona limestone does not extend south of Charlottesville, and in the area southwest of it the Martic thrust-block is separated from the Blue Ridge anticlinorium by normal faults of Triassic age. These normal faults extend southwestward across the folds of the anticlinorium, and the down-dropped Martic block becomes wider toward the southwest, as the anticlinorium becomes narrower. The width of that block is increased south of Maryland also, because the Coastal Plain sediments that form the southeast border of the Martic block swing southeastward away from the structural southwest trend of the older rocks. Along a section from Raleigh, North

[3] Arthur Keith: U. S. Geol. Survey Geol. Atlas, Mount Mitchell Folio (No. 124), 1905, p. 5.

Carolina, to Roanoke, Virginia the Martic block is 100 miles wide and the anticlinorium is 25 miles wide.

The Catoctin-Blue Ridge anticlinorium at Potomac River is composed of two anticlines of pre-Cambrian rocks and three synclines of Lower Cambrian slates and quartzites. The eastern syncline, which forms Catoctin Mountain, is faulted out at Warrenton, Virginia. The central syncline of South Mountain-Short Hills extends nearly to Lynchburg. The western syncline, which enters Virginia east of Harpers Ferry, continues across Virginia, but is cut out at many places by the thrust-fault that carries the rocks of the anticlinorium northwestward over those of the valley. Southwest of Natural Bridge, Virginia, thrust-blocks are piled one on another, and along a section of the Appalachian belt from Raleigh, North Carolina, through Roanoke, Virginia, to the West Virginia line there is not an autochthonous block.

Extent of Area of Thrust-faulting

The three sections just described show that thrust-faults are numerous in the area of the metamorphosed rocks of the Appalachian from New Jersey to North Carolina. Thrust-faults are numerous also in the Appalachian Valley west of this area, except in southern Maryland and northern Virginia, where few have been traced. A study of the structure of the Appalachians from New Jersey to North Carolina does not bear out the generalization of Keith,[4] that in this area "folds prevail and faults are rare." The belt of prevailing folds should be restricted to the valley region, extending from the axis of the Baltimore-Harrisburg salient across western Maryland into northern Virginia. It is not yet known with certainty that the Appalachian Valley of Virginia northeast of Natural Bridge is not faulted as well as folded, for detailed stratigraphic work in that area has not been completed.

Relation of the Martic Thrust-block to the Highland-Blue Ridge Anticlinorium

The existence of the Martic thrust was demonstrated in Pennsylvania by the discordant relation of the pre-Cambrian Wissahickon schist to the underlying Lower Cambrian quartzite and limestone and Ordovician limestones. Exposures of the fault-plane are few and poor in Pennsylvania and do not in themselves furnish conclusive evidence of thrusting, and no exposure of the fault-plane has been seen in Maryland or Virginia. South of Charlottesville the pre-Cambrian rocks of the Martic

[4] Arthur Keith: Structural symmetry in North America. Bull. Geol. Soc. Amer., vol. 39, 1928, p. 337.

block are separated from the pre-Cambrian rocks of the Blue Ridge anticlinorium by a normal fault. South of Lynchburg this fault separates pre-Cambrian rocks of nearly the same age and of similar character in the two blocks that lie on either side of the fault—the Lynchburg gneiss on the northwest and the garnetiferous Wissahickon mica schist of the Martic block on the southeast. This fault is not marked by any topographic feature, and the two formations can only be distinguished by the character of their metamorphism.

The Lynchburg gneiss is a granoblastic garnetiferous biotite gneiss that resembles the granoblastic oligoclase mica gneiss facies of the Wissahickon formation, but it does not contain the quartzite member that is characteristic of the Wissahickon. It does not resemble the pre-Glenarm Baltimore gneiss. The Lynchburg gneiss is the oldest rock exposed in the Blue Ridge-Catoctin anticlinorium and, with the exception of the white marble that resembles the Cockeysville marble, it is the only pre-Cambrian sedimentary formation in the anticlinorium southwest of Susquehanna River, but no evidence of its exact age has yet been found. It may be as old as the Baltimore gneiss or it may be younger and of Glenarm age. It is a pre-Cambrian gneiss whose mineral assemblage shows high-grade metamorphism and, doubtless owing to its deep-seated position up to the end of Paleozoic time and prior to the post-Triassic uplift, it has been preserved from retrogressive metamorphism.

The Wissahickon formation of the Martic block occurs in two metamorphic facies—the southeastern, an oligoclase biotite schist facies, and a northwestern, an albite chlorite schist facies, which forms the northwestern part of the thrust-block in Pennsylvania, Maryland, and northern Virginia.

Diaphthoritic Zones

Southwest of Appomattox Courthouse the Wissahickon formation is a garnetiferous biotite schist or gneiss containing staurolite in places. This area of biotite schist lies northwest of the Danville Triassic area and extends through Martinsville and Stuart, Virginia. It contains three zones of garnetiferous mica schist, with staurolite, which forms marked ridges or mountains. The southeastern zone extends through Long Mountain, northeast of Rustburg; the central zone forms Turkeyfoot Mountain and extends southwestward into North Carolina near Nettle Ridge; and the northwestern zone is exposed in Chestnut, Bull, and Carter Mountains, extending to a point just north of Mount Airy, North Carolina. The schist of these zones contains considerable chlorite and weathers green. Thin-sections show that the chlorite is secondary

to biotite, that both garnets and staurolite are cataclastically deformed and altered to chlorite in the cracks and on the edges, and that the biotite is frayed and drawn ou. Porphyroblasts of muscovite are abundant, and their random orientation indicates that they are younger than the foliation of the rocks. The schist is made up of minerals, such as biotite, garnet, and staurolite, that are products of metamorphism in a deep zone and of chlorite and muscovite, characteristic of metamorphism in a higher zone. The deep zone minerals belong to an earlier period of metamorphism in this rock, which has undergone retrogressive metamorphism in a higher zone during a later period of stress. The schist is therefore a diaphthorite, such as would be produced by mylonitization and crystallization of the biotite schist in a zone of thrusting. The repetition of diaphthoritic zones may indicate the imbricate nature of the movement.

Similar phyllitic schists showing retrogressive metamorphism occur in the Berkshire schist of the southern Taconic area, as described by E. B. Knopf [5] in a report on her study of the northeastern continuation of the Glenarm series in New England and its relation to the rocks of the Highland anticlinorium. She points out that such phyllites develop in a zone of thrusting as a result of mylonitization and subsequent crystallization under diaphthoritic conditions.

Evidence of thrusting is difficult to find in metamorphosed crystalline schist, and it is possible that many thrust-faults in the central Appalachians may have not been recognized. The presence of these diaphthoritic schists in the Martic overthrust block southeast of the Lynchburg gneiss makes possible the separation of the rocks of the thrust-block from those of the anticlinorium in a region where other evidences of overthrusting has been obliterated by metamorphism and later deformation. The diaphthoritic zone on the southeast side of the Peach Bottom syncline, which extends from southern Pennsylvania across Maryland and into Virginia near James River, also suggests a fault. In this zone garnet is altered to chlorite, and the greatly crumpled mica in the granoblastic quartz-chlorite muscovite schist of the Peters Creek formation is also altered to chlorite. The reversal of metamorphism, however, is the only evidence of thrusting seen along this zone.

Age of the Martic Thrust-fault

The Martic thrust is younger than the folding of the Conestoga limestone, of Chazyan age, which it bevels. It is older than the latest Appa-

[5] E. B. Knopf: Some results of recent work in the southern Taconic area. Amer. Jour. Sci., vol. 14, December, 1927, pp. 449-458.

lachian folding, for its fault-plane is folded. Therefore nothing more definite as to its age can yet be said than that it may be post-Ordovician—that is, Taconic, Caledonian, or Appalachian. This thrust-fault is probably older than the series of thrust-faults that parallel it on the northwest, in the anticlinorium and the Appalachian Valley. Near Roanoke, Virginia, these faults cut Mississippian rocks and are therefore probably post-Carboniferous. It may be that the Martic thrust belongs to the early part of the Appalachian deformation.

The Glenarm rocks of the Martic thrust-block were formed in the eastern part of the Appalachian Proterozoic geosyncline. Out of this geosyncline arose the geanticline of Appalachia at the end of pre-Cambrian time. The remnants of Paleozoic sediments still preserved show that Appalachia received Lower Cambrian and Ordovician sediments. In order to account for the load [6] of at least 10,000 feet of sediments under which the thrusting of the Martic block is supposed to have taken place, it has been suggested that the area received a considerable thickness of Silurian and Devonian sediments as well. There is no evidence to support this suggestion, however, for the nearest record of late Ordovician, Silurian, and Devonian sedimentation occurs in the Appalachian Valley west of the Blue Ridge anticlinorium.

Appalachia is considered the southwestern extension of Acadia of New England, but Appalachia has not been so well preserved as Acadia. The Martic thrust-block may represent a western part of Appalachia and the eastern part may be covered by Coastal Plain sediments. A large part of it probably foundered into the Atlantic Basin during the continental disruption which began in eastern North America in Jurassic and continued in Tertiary time. The only suggestion that eastern Appalachia may have contained a Paleozoic geosyncline which was the southern analogue of the Acadian of eastern Connecticut and Massachusetts is the occurrence [7] in a deep well near Ocala, Florida, of dark sericitic quartzite and light-green sericitic quartzite at depths between 4,100 and 6,100 feet. The appearance of the quartzite indicates that it is probably Paleozoic. Gunter [8] calls some of this material "micaceous schist," but the writer prefers for it the term sericitic quartzite and considers from its appearance that it may be Paleozoic, perhaps Cambrian.

[6] E. B. Knopf and A. I. Jonas: Geology of the McCalls Ferry-Quarryville district, Pa. U. S. Geol. Survey Bull. 799, 1929.

[7] C. W. Cooke: Geology of Florida. Abstract, Bull. Geol. Soc. Amer., vol. 40, 1928.

[8] Herman Gunter: Basement rocks encountered in a well in Florida. Bull. Amer. Assoc. Pet. Geol., vol. 12, number 11, November, 1928, pp. 1107-8.

GRANITES

GENERAL STATEMENT

The intrusive rocks in the Martic overthrust block and in the anticlinorium are of two types: (1) metamorphosed rocks of varied composition, made schistose by pressure, and (2) slightly deformed intrusive rocks, largely granites. The metamorphosed intrusives of the anticlinorium are overlain unconformably by Lower Cambrian rocks and are therefore pre-Cambrian. Those of the Martic thrust-block are not in contact with Lower Cambrian rocks, but in places are unconformably overlain by Ordovician slate and are therefore pre-Ordovician. The distribution and the age of the younger granites are of interest because Keith [9] has regarded these granites as having furnished the force for Appalachian folding.

GRANITES OF THE MARTIC THRUST-BLOCK

The most northerly little-deformed granite in the Martic thrust-block is the Woodstock granite, which occurs in small areas west and southwest of Baltimore, Maryland. Other granite of similar texture is found 75 miles farther southwest, along the same strike, near Fredericksburg, Virginia, but it is less calcic and lacks allanite, the characteristic constituent of the Woodstock granite, and was probably not derived from the same magma. The granite of the Fredericksburg area resembles the Petersburg granite, which begins south of North Anna River and extends through Richmond and Petersburg into North Carolina. Smaller areas of a similar granite occur in southern Virginia near Baskerville, Red Oak, Chatham, and Leatherwood. These areas extend into North Carolina in both the eastern and western part of the Martic thrust-block, and a large area of similar granite lies between them in North Carolina, in the neighborhood of Greensboro and Salisbury.

GRANITES OF THE ANTICLINORIUM

All the pre-Triassic intrusive rocks of the Highland belt northeast of Susquehanna River in Pennsylvania are of known pre-Cambrian age. The Lower Paleozoic rocks near Mine Ridge Hill anticline and in the syncline south of it, which extends northeastward to Willow Grove, are locally metamorposed. A subjacent batholithic magma [10] has been suggested to explain this localization of metamorphism and the widespread

[9] Arthur Keith: Outlines of Appalachian structure. Bull. Geol. Soc. Amer., vol. 34, 1923, p. 365.

[10] E. B. Knopf and A. I. Jonas: Stratigraphy of the crystalline schists of Pennsylvania and Maryland. Amer. Jour. Sci., vol. 5, 1923, p. 60.

tourmalinization that extends through both Cambrian and Ordovician rocks, but if there was a post-Ordovician batholithic intrusion in the anticlinorium near Mine Ridge Hill, erosion has not yet exposed the igneous body.

No evidence of Paleozoic pneumatolysis or of undeformed granites has been found in the Blue Ridge anticlinorium from Susquehanna River southwestward across Pennsylvania, Maryland, and Virginia. Pegmatites whose lead-uranium ratio indicates [11] that they are of late Carboniferous age occur near Spruce Pine, North Carolina. Keith [12] has reported the occurrence of younger granite, the Whiteside granite, from the anticlinorium in southwestern North Carolina and Georgia and has correlated with it granite in the area of the Martic thrust-block near Hendersonville and Kings Mountain, in North and South Carolina.

Most of the younger granites of the Martic thrust-block occur south of central Virginia, where they intrude younger pre-Cambrian rocks. The small areas in Maryland occur in deeper rocks, in the oldest pre-Cambrian rocks as well as in the younger. In the anticlinorium they are known only south of central North Carolina, where they also intrude pre-Cambrian rocks. Whether they occur under the Coastal Plain area of Pennsylvania and Maryland in the Baltimore-Harrisburg salient, as postulated by Keith,[13] is a question that can not be determined.

AGE OF THE LITTLE-DEFORMED GRANITES

The little-deformed granites have a true granitic texture, and although in places they show cataclastic texture they lack the gneissic characters of the older granoblastic igneous rocks. They may be younger than the Martic overthrust, although no granite has been found intruding both the rocks of the underlying anticlinorium and those of the overlying Martic block where the two are in contact. They cut only pre-Cambrian crystalline schist; hence the intrusive relations give no positive evidence of age. They are, as has been said, much less metamorphosed than neighboring pre-Cambrian intrusives, and this relative freedom from deformation may mean that they are post-tectonic granites that were intruded after the last period of folding that affected the region and are post-Carboniferous; or possibly they may be older—that is, they may be epi-Ordovician—and their lack of greater deformation may be due to the fact that they did not lie in a zone of weakness during the

[11] Arthur Holmes and R. W. Lawson: Factors involved in the calculation of the ages of radioactive minerals. Amer. Jour. Sci., vol. 13, 5th ser., no. 76, 1927, p. 327.

[12] Arthur Keith: U. S. Geol. Survey Geol. Atlas, Pisgah Folio (No. 147).

[13] Arthur Keith: Structural symmetry in North America. Bull. Geol. Soc. Amer., vol. 39, 1928, p. 350.

later Appalachian orogenic movement and were therefore little affected by it.

Laney,[14] in his discussion of the veins that carry copper ore in the Virgilina district, concludes that the veins are younger than the folding and metamorphism of the volcanic rocks in which they occur and regards the Red Oak granite as the source of the ore-bearing solutions. He assigns the Red Oak granite and the ores to post-Carboniferous time, but, owing to the absence of Carboniferous rocks in the area, the assignment can not be proved.

If the younger granites caused Appalachian Mountain building, one would expect to find them distributed along the entire length of the Appalachian belt and not concentrated mainly in the area south of central Virginia, in the Martic thrust-block, and south of central North Carolina in the anticlinorium. The lack of wide distribution of the younger granites from Pennsylvania to the southwest and the absence of definite proof of their post-Permian age throw doubt on the hypothesis that batholithic intrusions produced Appalachian deformation.

[14] F. B. Laney: Geology of ore deposits of the Virgilina district of Virginia and North Carolina. Virginia Geol. Survey Bull. 14, 1917, pp. 58, 64, and 94.

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GEOMORPHIC VALUE OF RIVER GRAVEL[1]

BY MARIUS R. CAMPBELL

(*Read before the Society December 28, 1928*)

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ROCK MATERIAL HANDLED BY STREAMS

INTRODUCTION

No one seems to have considered the possibility of using river gravel to determine the geomorphic history of a region. Students of this science have been taught to depend entirely on earth forms produced by erosion and to a certain, though small, extent on the gradient and alignment of streams in interpreting geomorphic history; as a result, they have relied implicitly on such features to furnish answers to all of their questions. It is now time to turn our attention to other possible lines of evidence, and, in the writer's opinion, the rock materials transported and deposited by streams during a partial or complete cycle of development is the most promising line of evidence that is available and is the one that will be considered in this paper.

The materials to which the writer refers are those rounded fragments of hard rocks which are usually designated pebbles, cobbles, and boul-

[1] Manuscript received by the Secretary of the Society March 14, 1929.
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ders—or, collectively, gravel. The problem, then, before us is to determine when and under what conditions will streams form and transport gravel, and when and under what conditions will they deposit this gravel in such a position that it may be preserved for the use of the geomorphologist long after the rejuvenation of the streams of the region. Briefly stated, the object of the inquiry is to determine, if possible, whether or not gravel found in many places far above stream level is a reliable indication of the stage of development of the stream which deposited it, and also whether or not it was once a continuous deposit and may be used with safety in determining earth crustal movements that have taken place since the gravel was laid down.

The main part of the problem, as stated above, is naturally divisible into three parts, as follows: (1) supply of materials, (2) transportation, and (3) deposition. These three phases of the subject will now be considered in the order in which they are stated above.

SUPPLY OF MATERIALS

In order to consider this question satisfactorily, it is necessary first to consider briefly what constitutes a cycle in the development of a stream and what are the conditions under which a stream operates in various stages of this cycle. One of the most brilliant concepts of William M. Davis, the acknowledged leader of American geomorphology, is that in which he likened the development of streams to that of a human being. He conceived a stream as originating on a new surface of the land, progressing by various stages of increasing activity and power until it reaches maturity,[2] and then declining gradually to a life of comparative inaction

[2] In order that the writer's use of the term maturity may be clearly understood, it seems best to devote a few lines to the meaning and use of this term. It is especially important at this time, in view of the recent statement by Bailey Willis (Bull. Geol. Soc. Amer., vol. 39, 1928, p. 504), that his term "matureland" "may be used to designate a landscape in any stage of maturity—vigorous, advanced, or subdued." According to this statement, Willis would apply the term maturity to the stage in which the landscape is subdued. The writer finds that many other geomorphologists follow this usage, which, however, does not agree with the original definition.

There can be but one governing principle in the introduction and use of a new technical term, and this is that the original definition shall hold, unless it can be shown that it is faulty or is not broad enough to cover the subject. William M. Davis was the first to use the term maturity in a geomorphic sense in 1884, but his first definition is rather sketchy. Four years later, however, he published a thoroughly satisfactory definition (Rivers and valleys of Pennsylvania, Nat. Geog. Mag., vol. 1, 1889, p. 206), as follows:

"Maturity seems to be a proper term to apply to this long enduring stage; for as in organic forms, where the term first came into use, it here also signifies the highest development of all the functions between a youth of endeavor towards better work and an old age of relinquishment of fullest powers. It is the mature river in which the rainfall is best led away to the sea, and which carries with it the greatest load

in extreme old age. This concept will form the basis of the present consideration of the work of streams.

A cycle of stream development begins when a new land surface is exposed to the action of the elements. This new surface may be the bed of a former sea or lake or it may be the featureless surface of extreme old age, developed in the closing stage of a previous cycle, or any other plain surface newly exposed to erosion.

On a new land surface, whatever its origin may have been, the water derived from precipitation gathers in depressions and, having filled them, seeks the lowest natural outlet to the sea. In this manner a stream is born. Like an infant, it lacks purpose, initiative, and strength and is guided largely by the obstructions that confront it and that determine the direction and the sinuosities of its course. It has no power to carve a channel of its own, and consequently its sluggish current has no part in supplying rock fragments which, at a later stage of the cycle, may be rounded into gravel.

Gradually the power of the infant stream is increased as its tributaries develop and work their way headward, until in youth it attains sufficient gradient and volume to begin the trenching of its once-even floor. This floor generally consists of incoherent material recently deposited or similar material produced by deep rock disintegration in the previous cycle of erosion. Under such conditions little or no coarse material is furnished from which gravel may be fashioned, but the incoherent material is soon removed and active excavation of hard rock is carried on by the stream, which, however, has a limited volume of water and performs its work in a restricted part of its drainage basin.

Gradually the stream passes this stage of its development by the continual extension of its head branches until all of the original flat land has been consumed. When this stage is reached the stream is at maturity, for it is removing more material than it removed before or ever will again and it is working at its utmost capacity. It is then that the greatest amount of material is excavated by the stream, and much of

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of land waste; it is at maturity that the regular descent and steady flow of the river is best developed, being the least delayed in lakes and least overhurried in impetuous falls."

Although this definition is very explicit and is susceptible of only one meaning, the one given by N. M. Fenneman (Geology of Cincinnati and vicinity, Ohio Geol. Survey, Bull. 19, 1916, p. 97) is more compact and precise. It is as follows:

"Maturity is therefore characterized by maximum dissection, maximum relief, maximum slopes, run-off, stream power, and load."

As the original definition given by Davis is accurate and covers the subject, it should stand and geomorphologists generally should accept it, unless they can show that it is faulty. The writer's use of terms denoting stages of an erosion cycle are the same as those proposed by Davis in his early papers.

this material is made up of fragments of hard rock, which, under abrasion during the process of transportation, will pass eventually through the various stages of reduction in size generally designated as boulders, cobbles, pebbles, and sand.

After maturity the excavating power of the stream begins to fail as the velocity of the current is checked in response to the reduction in the relief of the land. Mechanical erosion gradually gives place to chemical disintegration, and consequently a smaller and smaller percentage of the material excavated by the stream consists of fragments hard and coherent enough to form gravel. This stage, which for convenience may be termed post-mature, is the last one in which active excavation by the stream is possible.

Following the post-mature stage is one of general inactivity, called old age. In this stage the hard rocks that once constituted the surface of the land have been so deeply disintegrated by the action of the weather that they readily break down into their constituent mineral fragments, which are generally so small that, when rounded, they form only fine sand or silt. The gradient of the streams is too small and the current too weak to permit of any excavation except the scour of the banks in times of flood; but even this action is slight and produces little or no coarse material. In general, it is a stage of inactivity in all kinds of stream-work.

From the above statement regarding the conditions which permit of the excavation of bedrock, it is obvious that the supply of coarse, hard material from which gravel may be formed begins in the youthful stage of stream development and gradually increases up to the end of maturity; it then decreases through and practically ceases with the post-mature stage of development.

TRANSPORTATION

The transporting power of a stream varies greatly in the different stages of its geomorphic development. In the earliest stage, or that of infancy, it is slight, because much of the territory within the limits of its drainage basin is still in its original undissected condition, and, as a result, the transporting power of the current which under ordinary conditions is nil is only slightly accelerated in times of heavy rainfall or of melting snow. In this stage the stream is as inefficient as an infant and the amount of rock material carried by it is so small that it cuts no figure in the general work of transportation accomplished by the stream.

With the beginning of intrenchment, which characterizes the stage of youth, the gradient of the stream is greatly increased; but even then,

owing to the lack of dissection in its upper reaches, the water is not freely supplied to the part of the stream that is undergoing intrenchment, and consequently the amount of material transported by it is not so great as it will be at a later stage. The material that is supplied is generally coarser than it will be in a more advanced stage of the cycle, and as a result it is not so easily transported. Boulders of considerable size may be moved by the stream, but only for short distances, and they soon find resting places from which it is difficult to dislodge them. Here they will repose until the crest of some other flood reaches them, when the process will be repeated. Altogether, the transporting power of a young stream is not great, although the percentage of coarse material is large when compared with the total amount that is moved.

The maximum amount of transportation is accomplished in the next, or mature, stage of the cycle, for at this time all of the water supplied by precipitation, except a small amount that sinks into the soil, finds its way readily down the stream to the sea. The volume of water is greater and more constant than it was before and also than it will be again, and the rapid current is able to handle most of the material supplied to it. At this stge it will transport not only pebbles, but cobbles and, in times of great floods, even boulders of considerable size.

After maturity the slopes gradually decrease, less and less material is delivered to the master stream, and this stream, owing to its constantly decreasing gradient, gradually loses its power to transport such material as is brought to it. More and more of the rock material is deposited by the storm waters on a floodplain which at first is formed only where the stream is flowing on weak rocks, but, as time goes on, is developed also on the hard rocks of the valley as they are reduced to the level of the stream. By the end of the stage of post-maturity the stream is able to transport only a very small amount of coarse rock material and even the finer particles are carried forward only during the flood stage of the river.

When old age is reached the master stream carries only a very small quantity of coarse material, except such as may be transported on floating cakes of ice or uprooted trees, and this is generally so small as to be negligible. In general it may be said that in this stage the transportation of coarse material has ceased, and hence the work performed by a stream in old age need not be considered in connection with the problem now before us.

The statements so for given regarding transportation may be summarized as follows: In infancy a stream is powerless to transport rock

waste, even though water is supplied to it in great abundance; in youth its power to transport such material increases rapidly and reaches a maximum in the stage called maturity; following maturity its transporting power begins to wane and its ability to handle coarse material practically ceases by the close of the post-mature stage.

DEPOSITION

General conditions.—Deposition occurs in all stages of the cycle in which transportation is actively going on, but the kind of material, as well as the manner in which deposition takes place, varies greatly in the different stages.

Thus in the youthful stage the current is irregular, being very swift in places of sharp descent and comparatively sluggish in the intervening reaches of quiet water. In the former localities boulders of considerable size may be picked up or rolled along the bottom, but as soon as they reach the more quiet water of intervening reaches they are dropped and the current is unable to move them until the conditions of gradient or volume of the stream is altered. In this stage only coarse material is deposited and deposition takes place only in the immediate bed of the stream.

This condition holds throughout youth and maturity, but in the last-mentioned stage the material that is transported is finer, the individual fragments seldom being of sufficient size to be designated as boulders. The aggregate load of the stream and the amount of material deposited, however, increase steadily until their peak is reached at maturity, which, in the words of Fenneman, "is characterized by maximum dissection, maximum relief, maximum slopes, run-off, stream power, and load." In the closing stages of maturity the stream begins to widen its valley bottom in the softer rocks and, as it does so, deposits permanently some of the coarse material, such as cobbles and pebbles, that it has rolled along the bottom.

The building of a floodplain, begun at the close of maturity, is continued and enlarged during the succeeding stage of post-maturity, as the width of the valley bottom is increased in the areas of soft rocks to many times that of the bed of the stream, and even in the areas of hard rocks to a width appreciably greater than that of the stream which built it. Coincident with the widening of the valley bottom and the decrease in the gradient of the stream comes a great increase in the deposition of coarse material and a smaller increase in the amount of fine material deposited. As this is a most important epoch in the development of the stream, its work will be described in greater detail.

The building of a floodplain is coincident with the widening of the floor of the valley by lateral swing of the stream in its meanders. As the stream swings farther and farther from the axial line of its meander belt, it tends to increase the width of that belt and at the same time deposit a large part of its load of coarse material in the parts of the bed that are constantly being abandoned. The coarse material is first deposited, but this is covered in times of flood with relatively stagnant water, from which the fine earthy material is gradually precipitated in the form of fine sand and silt.

In course of time this process is repeated in all parts of the newly developed floodplain, as the meanders gradually but irresistibly move down valley, and all parts of the floodplain are made up of first a pavement of coarse cobbles and pebbles and then a covering of sand or silt. By the process outlined above practically all parts of a well developed floodplain are underlain by a sheet of gravel which is continuous and which, if preserved, would be of the greatest value in interpreting the geomorphic history of the region.

Toward the close of post-maturity the stream meanders more and more widely, and much of the gravel previously deposited is reworked and redeposited and in this process is abraded, becoming finer and finer until, at the beginning of old age, but little coarse material is being handled by the stream, except such as may be borne to it on cakes of ice or on floating trees. This, however, is generally so small in amount as to be negligible in a general consideration of stream-work. A great amount of material is deposited in this stage of the cycle, but it generally consists of sand and silt too fine to be classed in the category of gravel.

The work of deposition of a stream may, therefore, be generalized as follows: Deposition takes place in all stages of a cycle of development except in infancy. In youth it begins, but throughout that stage it is restricted, as to the coarseness of the material, to the amount deposited and to area covered. Similar conditions hold for maturity, except that the material deposited rarely include boulders and the area covered by it is somewhat greater, owing to the slight development of a narrow floodplain and to the broadening of the bed of the stream. In post-maturity the greatest amount of coarse material is laid down, but this material generally includes only pebbles and cobbles instead of the larger fragments, called boulders, which are common in beds deposited in preceding stages. The area of deposition is greatly increased by the increase in width and extent of floodplain. This is the time of greatest deposit of coarse material and the time of most continuous unbroken deposition

throughout the entire extent of the stream. In old age deposition is great, but the material is so fine that it does not come within the class here being considered.

Preservation of deposits.—The production, transportation, and deposition of gravel by a stream is of little geomorphic importance unless the gravel beds or their individual components are preserved in place for future reference. The most important part of the problem is, therefore, to determine the conditions which will permit of the preservation of deposits of stream gravel during and after the rejuvenation of the drainage system that originally supplied it. Since transportation and deposition of coarse rounded material begin in the youthful stage of the cycle of stream development and continue through several of the succeeding stages, it is desirable to consider the character of the deposits made in each stage, to see whether or not they are of such a character or in such a position as to be preserved for future inspection.

The material deposited in the youthful stage of a stream is generally very coarse and would afford an excellent key to the condition of the stream which deposited it, provided there is a possibility of its preservation. This phase of the problem can easily be solved by considering the conditions under which such a stream operates. As has been shown previously, a youthful stream is flowing in a valley whose bottom is but little, if any, wider than the bed of the stream. Under such conditions all of the material which is deposited will be laid down on the immediate bed and will be the first to be removed when the transporting power of the stream is increased by rejuvenation. Therefore it is useless to look for or expect to find any continuous bed of gravel deposited by a youthful stream after that stream has passed into a succeeding cycle.

There are some seeming exceptions to this general rule. These are: (1) When the deposit is in the form of an alluval cone, (2) when it is a delta built by the stream in a lake or the sea, and (3) when it takes the form of an inherited and intrenched meander, cut off by lateral erosion and abandoned by the stream. In the first case a cone of detrital material is generally deposited where a youthful stream emerges from a mountainous region to flow on a surface of low relief; this cone is composed of the coarsest material carried by the stream, and if it grows to any appreciable size it will be trenched when the drainage system is rejuvenated, but probably some of the material will remain to mark its position and character. In the second case the cone, instead of being built on the land, as in the previous example, is deposited in standing water in the form of a delta. On rejuvenation following uplift of the

land the delta will become a surface feature and will be subject to the vicissitudes of subaerial erosion. If it is small it may be entirely removed, but if it is of considerable size the stream may merely cut a trench through it, leaving the marginal remnants of gravel and sand to record the event. Similar results are produced when an intrenched meander is abandoned, because the bed of the stream, even in a youthful stage, is floored with boulders and cobbles, and when the cut-off is effected the rounded material left in the abandoned loop of the meander will remain indefinitely as a record of the event. As, however, the building of an alluvial cone, the deposition of material in the form of a delta, and the cutting off of an inherited meander do not characterize any particular stage of a cycle, the gravel deposited in them will not necessarily coincide in altitude or be a part of any continuous gravel deposit, and therefore will have very little geomorphic value. It is important, however, for an investigator, making a field examination, to have constantly in mind the possibility that some of the gravel found by him may have been laid down in such sporadic deposits.

During the stage of maturity the conditions are essentially the same as those just described for youth. All of the streams are depositing an abundance of coarse material, but they drop this material on the bed or bottom of the channel they occupy. If it could be preserved through later cycles of stream development, it would be of the greatest value to geomorphologists; but, since it is mainly confined to the bottom of the channel occupied by the stream, rejuvenation will result only in giving the stream added power to pick it up and transport it to points lower down the valley and will not, under ordinary circumstances, leave any continuous deposit undisturbed on the adjacent banks or bluffs. The exceptions to the conditions noted above are the same as those described for youthful streams, and, though they may occur in any part of this stage of the cycle, they leave little or no information by which the geomorphologist may reconstruct the landscape that characterized the river basin at the time they were deposited. As a consequence, they have no more value than the exceptional deposits laid down by a youthful stream.

As previously stated, the amount of coarse, rounded material transported by a stream in the post-mature stage of the cycle is much less than that which was handled by the stream in its mature stage, but the material handled is deposited in such locations that it is not liable to be swept away when the stream is rejuvenated. This is due to the fact that most of the deposition going on in this stage of the cycle is on the floodplain of the stream, and this floodplain, however narrow it may be,

always adds an appreciable amount to the area on which deposition is taking place. In the early part of this stage the floodplain is generally narrow, but it increases very decidedly in width as the stage progresses. Under such conditions the rejuvenated stream would simply cut a valley in and through the material deposited to a depth corresponding to the amount of uplift suffered by the region. If the stream has built a floodplain only a little wider than its channel, rejuvenation might enable it to remove all of the gravel on one side of the channel, but in so doing it would permit more or less gravel to remain on the other side. If the floodplain were many times wider than the stream, the new channel, due to rejuvenation, might be bordered on both sides by gravel deposits of appreciable width, and hence, under such conditions, gravel may be expected to occur on the bluffs on either side of the stream at approximately the same altitude. This is the most favorable condition that can be imagined, and if it prevailed one would be justified in expecting to find gravel on almost every projecting point of the present upland that at the time of deposition was a part of the river floodplain.

There are no possible exceptions in this stage of the cycle, such as have been mentioned as possibilities in the earlier stages of development. This is due to the fact that (1) no alluval cone will be built in the postmature stage of development, because the relief is so slight that the surface forms developed on hard rocks are very similar to those developed on soft rocks. The difference is merely one of degree, and this difference is so slight that it would not result in the forming of an alluvial cone of any appreciable size. (2) Delta-building will go on in this stage much as it progressed in the preceding stage, but the materials deposited on it will be practically continuous with the floodplain farther up the stream, and so the delta will be but the extension of the floodplain deposit, and when rejuvenation occurs can not be distinguished from it, except by its stratification. (3) Meanders may be cut off in the postmature stage as well as in any stage that has preceded it, but the coarse material left in the abandoned loop will be the same and continuous with the floodplain deposits both above and below the point where the cut-off occurs.

The stage of old age is characterized by a very wide floodplain, but the material deposited during this long stage is generally made up of fine sand or silt. Such material is not so easily preserved or identified as gravel, and consequently it is not so useful to the geomorphologist as the material deposited during an earlier stage. Another factor that enters into the problem and prevents the geomorphologist from depend-

ing on material deposited during the stage of old age is that this stage is seldom, if ever, reached by streams before they are rejuvenated by uplift or their valleys drowned by depression of the land. If such material could be found and if it could be identified with certainty as the material deposited by any given stream, then it would be of the greatest value in unraveling the secrets of the past; but these uncertainties are so great as practically to rule it out of consideration.

Deposits of coarse material made in the post-mature stage of the cycle are the ones most likely to be preserved, and, since they consist of remnants of material deposited on floodplains, may be correlated with other deposits, and thus linked together, giving a concrete picture of the conditions in the drainage basin as a whole at this particular stage. Accordingly, gravel deposited in this stage of the cycle may be accepted as reliable evidence regarding the conditions prevailing at the time of its deposition. Such deposits may not be characterized by boulders, but they certainly will consist largely of pebbles and to a small extent of cobbles. There will be no sporadic deposits at this stage; hence all of the gravel may be accepted as representing remnants of a former widely developed floodplain.

Although the floodplain from which the present rather widely separated masses of gravel were derived was doubtless originally of a fairly constant thickness in all its parts, except the extreme margins, the remnants that may be found today are so affected by weathering through the long ages that have elapsed since they were deposited that they are made up generally of scattered pebbles and cobbles which bear little resemblance to the original deposit. Also, it is probable that in the long time they have been exposed that they have gradually migrated down the slope, especially where they border a deeply intrenched stream whose slopes are exceedingly steep. It seems probable that under such conditions and in extreme cases the pebbles and cobbles may have moved down the slope as much as 100 feet below the level at which they were deposited. In many cases in the field the writer has found gravel strewing a slope throughout a zone 40 to 60 feet in vertical height, although it is probable that the original deposit from which they were derived did not have a thickness in excess of 10 or 15 feet. In such cases the safest procedure is to determine as accurately as possible the upper limit of the rounded material and to disregard the lower limit, which undoubtedly changes as the erosion of the slope progresses. The upper limit of gravel does not always occur at the same height, even in near-by areas; but this is not to be wondered at when one observes the difference in level, even on a

widely developed floodplain of today. Floodplains are not built in a day; they are the result of long-continued stream action, both in the nature of deposition and erosion, and some parts may be vastly older than other parts and occur at somewhat different levels.

From the foregoing statement it might be inferred that the uncertainty of determining the original position of present high-level gravel is so great as to render the gravel of little or no service in interpreting past events, but the experience of the writer makes him believe that most of the deposits, even where they have been exposed for countless ages on spurs of the upland which jut out nearly to the present stream channel and lie from 400 to 500 feet above it, have not moved appreciably, and that their upper limits can generally be determined with a reasonable degree of certainty. Minor discordances in altitude are to be expected, and several of them were found in actual experience, but on the whole the writer was more impressed with the seeming regularity and accordance of altitudes than he was with the discordances. In a few cases it was evident from the character of the deposit, as well as from its position, that the gravel had migrated down the slope; but when the observations were plotted on a vertical section, the discordance of these deposits in vertical position was generally so great as at once to attract one's attention and brand them as exceptional and unreliable.

Structural Interpretation of Results

Correction for original gradient

The next important phase of the subject is the method by which the character and amount of crustal deformation may be determined from deposits of gravel that have been left high above the surface of a rejuvenated stream.

From the preceding statement of the conditions, it is apparent that a more or less continuous bed of gravel implies the former existence of a floodplain, which in turn indicates that the stream which deposited it was in the post-mature stage of its cycle of development. Such a floodplain must necessarily have had, when it was formed, a general slope downward toward the mouth of the stream, but if it has been deformed by subsequent movements, the present position of the remnants is due to their original positions in the sloping floodplain plus or minus the amount of deformation that has taken place at that particular point. If, therefore, the original height above sealevel, or any other convenient datum, of any particular point in the old floodplain is known and also

its present height, then the amount and character of the deformation at that particular point will be the difference between the two elevations.

The problem thus resolves itself into the determination of the gradient of the old floodplain, of which the high-level gravels of today are but the scattering remnants. The obvious method of doing this is to determine the gradient of a stream that today is in the post-mature stage of its development. At first sight this might seem to be a very simple procedure, but when the attempt is made to find such a stream many difficulties are encountered. In the first place, it is difficult to find a stream that has passed through all of the early stages of its development, up to that which the writer calls post-maturity, without having been interfered with in some way, either by rejuvenation through the uplift of the land or drowned, if such an expression is permissible, by subsidence, or has been interrupted in its development by some untoward condition, such as the invasion of a glacier or a flow of molten lava.

Not only should one endeavor to find a stream in the stage of post-maturity, but he should find two—one which represents conditions at the beginning of this stage and another the conditions at its close. In other words, one should have an example of a stream which represents conditions at the beginning of the formation of a continuous floodplain and another which represents the close of gravel deposition. The first one will probably be characterized by a wide development of its valley floor and its corresponding floodplain where it is situated on soft rocks, but by only a narrow floodplain where it flows on very hard rocks, if, indeed, it has widened its valley floor appreciably in such situations. In the second case the floodplain will be very extensive on soft rocks, but restricted on hard rocks to a width of not less than three times the normal width of the channel of the stream. Where shall we find streams showing these characteristics?

To the writer it seems probable that the rivers on the Gulf coastal plain east of Mississippi River are more nearly in the condition of early post-maturity than any other streams in the United States, and that the probabilities are in favor of little, if any, crustal movement having taken place in this region in recent geologic time. It is true that the streams in this region are not so old, if age should be reckoned in years, as many other streams in the country, but they are flowing on weaker rocks, across a wide belt of the coastal plain, and therefore are in a comparatively advanced stage of their geomorphic development. Because of this condition, Alabama River is taken as the best example of a stream in the early stage of post-maturity that is available.

Alabama River enters tide water at Mobile, and it is crossed by the 100-foot contour line about 170 miles above this point. This, although recognized by the writer as a crude measurement, gives a gradient of about 7 inches to the mile. It appears reasonable, therefore, to assume that the gradient of a stream which is in a condition to deposit gravel on a narrow floodplain throughout most of its course on rocks of moderate hardness has about this gradient.

The gradient of a stream that has developed a much wider floodplain, say three or four times the actual width of the stream channel, on hard rocks must necessarily be much less, and, for the sake of completing the analysis, will be considered as 3 inches to the mile. It is realized that these figures have little weight and are based on insufficient evidence, but they will be accepted as approximately correct until more direct data bearing on the question are available.

Stream gradients of 7 and 3 inches will therefore be tentatively accepted as characterizing streams in the early and late post-mature stages of development. If a bed of gravel or the remnants of such a bed are found having a present downstream gradient within the limits specified above, this fact may be taken as indicating that there has been no marked deformation since its deposition, although crustal movements resulting in the uplifting of the region may have occurred. If the gradient is greater or less than the figures given above, or if it is in the opposite direction—that is, descending in altitude up the stream—then it may be assumed that there has been crustal movement which resulted in the deformation of the bed of gravel. If two beds of gravel are found at different altitudes in the valley of a river of considerable size, then it is highly essential for the geologist to analyze his problem very carefully to determine just what the two beds represent and what is their relationship one to another. It can hardly be expected that two distinct beds of gravel will be preserved unless the higher gravel represents a much more advanced stage of river development than does the lower, because if they represent similar stages of development the cutting of the stream at the time of deposition of the later gravel would undoubtedly remove most, if not all, of the upper or older gravel. Because of this fact, it may be taken as axiomatic that two distinct beds of gravel represent stages of different cycles, and that the older and high gravel is the result of deposition in a later stage of development of the stream than the lower and younger gravel.

PRACTICAL TEST OF THEORY

In the past summer the writer, through the cooperation of Dr. George H. Ashley, State Geologist of Pennsylvania, had an opportunity to make a field test of the geomorphic value of high level gravels which were deposited by Susquehanna River in the Piedmont section below Harrisburg in previous cycles of its development.[3] These beds of gravel must have been at the time of their deposition practically continuous throughout this portion of the river valley, for their remnants today, although in places miles apart, are of such accordant heights and their interrelation is so constant as to permit of no other explanation.

The beds of gravel in question are higher, and therefore older, than those generally recognized in this region as of Pleistocene age, and this determination of age relationship is confirmed by the deeply weathered condition of the individual pebbles and cobbles composing them. The older bed, as developed in the vicinity of Havre de Grace, at the mouth of the river, has been generally recognized as of Tertiary age and equivalent to the Bryn Mawr gravel in the type locality.[4] It is now generally recognized as probably of early Pliocene age. The lower and younger gravel is without question equivalent to the gravel formation present at the village of Brandywine, about 15 miles southeast of Washington, to which the name Brandywine has been restricted since 1924. Its age has not been positively fixed, but Clark regarded it as probably earliest Pleistocene, although there is a possibility that it may have been deposited in the closing stages of the Pliocene epoch.

In tracing the remnants of these gravel beds up Susquehanna River from Havre de Grace, it was found that the lower, or Brandywine, bed, which at the mouth of the river has a present altitude of 300 feet above tide water, rises gradually, but with some slight irregularities, up the stream until at Harrisburg it attains an altitude of 430 feet. In striking contrast to the fairly regular upstream rise of this gravel bed is the marked irregularity of the remnants of the Bryn Mawr gravel. This bed near the mouth of the river is at an altitude of 400 feet above tide. It rises in a continuous exposure of nearly 5 miles to a height of 460 feet. Beyond this exposure, owing to the weakness of the schist which underlies it, the surface for a distance of 15 miles has been worn down by erosion until all traces of this bed have been removed, except a single exposure

[3] For graphic representation of the results of this work, see "Late Geologic deformation of the Appalachian Piedmont, as determined by river gravels." Proc. Nat. Acad. of Sci., vol. 15, no. 2, 1929, pp. 156-161.

[4] The resuscitation of the term Bryn Mawr gravel, by F. Bascom, U. S. Geol. Survey. Prof. Paper 132-H, 1924.

on the top of a hill near the Maryland-Pennsylvania State line. The correlation of this isolated outcrop with the gravel near the mouth of the stream would be hazardous were it not for the fact that the Brandywine gravel below it was traced across the intervening territory with a sufficient number of exposures to make its identification almost certain. The evidence afforded by the Brandywine gravel, coupled with the fact that no other continuous bed of gravel except the Bryn Mawr is known above the Brandywine, makes the identification of the gravel on the lone hilltop fairly satisfactory.

In Pennsylvania the remnants of the Bryn Mawr gravel continue to rise upstream until they reach a maximum of 660 feet in the vicinity of Safe Harbor, at the mouth of Piqua Creek. From this maximum altitude the gravel descends upstream to 630 feet at Turkey Rock, 580 feet on the high ridge south of Columbia, 560 feet on Chickies Rock just north of Columbia, and 540 feet at the mouth of Codorus Creek. For some distance above Codorus Creek the altitude is nearly constant, but it appears to be slightly below 500 feet at Middletown, and consequently this is regarded as the lowest point reached by the Bryn Mawr gravel above Safe Harbor. Above Middletown the rise upstream is very slight as far as the mouth of Juniata River, but above this point it rises steadily, under the influence of the great Appalachian upwarp, whose axis lies near the Allegheny front.

From the peculiar relationship of these two gravel beds below Harrisburg, it seems to the writer evident that the Bryn Mawr gravel, which must have been deposited with a slight gradient downstream, suffered deformation before the Brandywine gravel was deposited by an uplift whose axis crossed the river near Safe Harbor. The amount of uplift, measured by the present distance between the two beds at Safe Harbor, is about 270 feet; but this measurement is not accurate, as it does not allow for the original gradients of the two beds at the time they were deposited. Fortunately, in this case one is able to determine roughly the stage of development of the river in each of these periods of gravel deposition. This is made possible by the existence of a belt of high land presumably caused by more resistant rocks in the vicinity of Safe Harbor and McCalls Ferry than there is either above or below these places. In this upland, which now rises to altitudes ranging from 750 to 800 feet, the width of the Susquehanna Valley bottom and floodplain at the time of Bryn Mawr deposition was about three times that of the present stream; but in Brandywine time the width was not appreciably greater than it is today. On the soft rocks, such as limestones and weak shale, the width

of the valley bottom was very much greater—in fact, was so great that at this late date it is impossible to determine their limits, either at the time of Bryn Mawr deposition or when the later and lower gravel was laid down.

The broad valley floor and floodplain in Bryn Mawr time clearly indicates that the development of Susquehanna River had then reached nearly to the end of the stage of post-maturity, but had not attained the stage of old age and the formation of a peneplain. In the time of Brandywine deposition the river did not succeed in broadening its valley bottom where it was flowing over very hard rocks, and consequently it had in such a locality a very meager floodplain. This indicates a much earlier stage in the cycle of development than is implied by the conditions attending the deposition of the Bryn Mawr gravel and roughly may be regarded as early post-maturity.

If, therefore, we accept three inches as the normal gradient per mile for a stream in the stage of late post-maturity, then all figures representing the altitude of the Bryn Mawr gravel above sealevel in the Susquehanna section, except at the mouth of the river, should be reduced by an amount equal to the distance in miles from tide water multiplied by the assumed gradient per mile—three inches. Thus the Bryn Mawr gravel at Harrisburg has a present altitude of 520 feet; when the gravel was deposited its altitude was 70 (miles) times 3 (inches), or 18 feet less, or approximately 500 feet above tidelevel. The present altitude of the Brandywine gravel at the same place is 430 feet. When this gravel was deposited its altitude was 40 feet less, or 390 feet above tide.

The amount of uplift which the Bryn Mawr gravel suffered in the interval between its deposition and that of the Brandywine gravel is 100 feet at the mouth of the river, 280 feet at Safe Harbor, 130 feet at Middletown, and 110 feet at Harrisburg. This uplift was evidently in the form of an anticline whose axis crossed the river at Safe Harbor and probably extended southwest and northeast, in general conformity with the trend of the folds in the Paleozoic rocks.

As the conclusion reached from this line of geomorphic evidence is diametrically opposed to the prevailing idea that all uplifts in this region are parts of giant upwarps whose axes corresponded with the general axis of elevation of the Appalachian Highlands, it will doubtless fail to meet with general approval; but the writer feels satisfied that the facts on the ground can not logically be interpreted in any other way, consequently he welcomes suggestions and criticisms on every point he has presented.

The result of the study of the gravels of the Susquehanna River was so conclusive that similar studies were carried on along the Potomac and Schuylkill rivers. This work showed a similar, though smaller, anticlinal fold in the Bryn Mawr gravel, crossing Potomac River just above Great Falls, and possibly one on Schuylkill River, in the vicinity of Norristown; but the surface of the adjacent land between Norristown and Reading is so low that there is no possibility of finding any remnants of the Bryn Mawr gravel to prove or disprove this hypothesis. All that can be said of the evidence along this river is that it is susceptible of an interpretation in harmony with the conclusions reached by a study of the gravel of the other streams.

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AGE OF LAKE LAHONTAN [1]

BY J CLAUDE JONES

(*Read before the Society December 29, 1928*)

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DEFINITION OF LAKE LAHONTAN

Lake Lahontan is here used as the name of the old lake that formed the tufa, beaches, bars, and other shore features now visible in its basin and that deposited the sediment exposed in the canyons of the present streams of the basin. This is the sense in which the name was used by King, Russell, and Antevs.

STATEMENT OF THE PROBLEM

A recent attack[2] on the problem of the age of the lake by three geologists led to diverse conclusions. The points agreed on are:

1. The deposition of the tufa by algæ does not necessitate a strongly saline solution, as Russell[3] supposed.

2. Lake Lahontan had three periods of flood and intervening periods of low water.

3. Lake Lahontan was never completely desiccated; otherwise the Lahontan fish that still live in Pyramid Lake would have been exterminated.

4. Walker Lake became a part of Lake Lahontan only after the second and highest stage of flood.

5. The gravel under the Lahontan beds in the valleys of the Humboldt and Walker rivers are pre-lacustrine alluvial fans. Russell was mistaken

[1] Manuscript received by the Secretary of the Geological Society December 12, 1928.

[2] J. C. Jones, Ernst Antevs, and Ellsworth Huntington: Quaternary climates. Carnegie Institution, Pub. 352, 1925.

[3] I. C. Russell: Lake Lahontan. U. S. Geological Survey, Mono. 11, 1885.

in correlating them with the medial gravels found in the canyon of the Truckee River.

6. The Sequoia curve worked out by Huntington[4] is a climatic record,

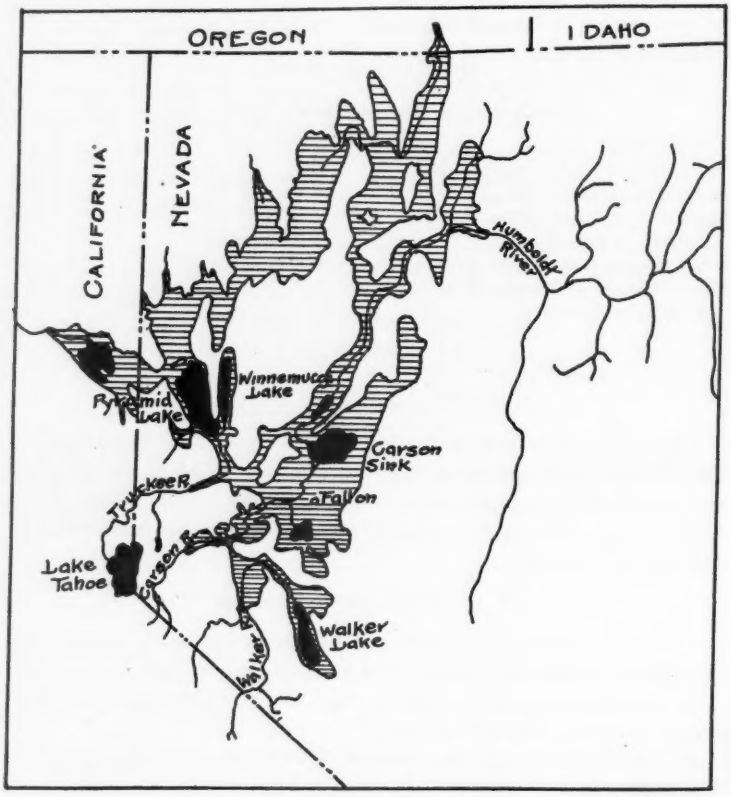

FIGURE 1—*Lake Lahontan*

Parallel lines indicate limits of ancient lake. Black areas are existing lakes.

but Antevs does not agree that rainfall has been the largest factor in determining the width of the annual rings of the trees.

The major disagreement concerns the correlation of the lake cycles with the Sequoia curve (Jones) or with stages of the Pleistocene glaciation (Antevs and Huntington).

[4] Ellsworth Huntington: The climatic factor as illustrated in North America. Carnegie Institution, Pub. 192, 1914, p. 172.

Lahontan Sediments

Among the large number of records of wells that have been drilled in the sediments of the Lahontan Basin, that of the Timberlake well,[5] drilled

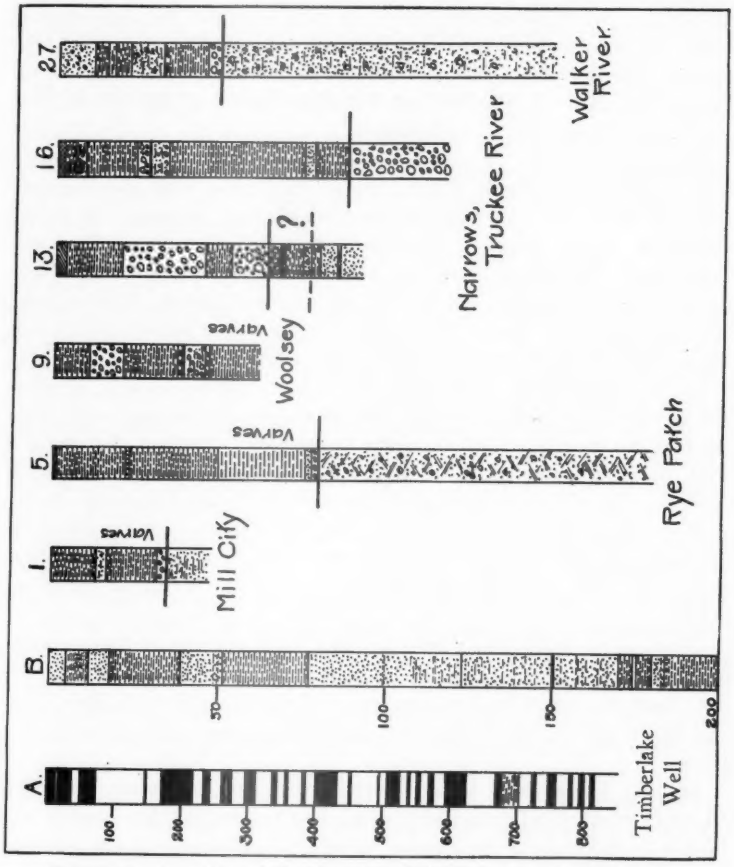

FIGURE 2.—*Comparison of the Log of the Timberlake Well and Sections of Lahontan Sediments*

In section A the clay beds are solid black; in the other sections they are ruled.

10 miles north of Fallon by the United States Geological Survey, is the most accurate and detailed. In the accompanying diagram (figure 2),

[5] H. S. Gale: The search for potash in the desert basin region. U. S. Geological Survey Bull. 530, 1913, pp. 306-311.

section B represents the upper 200 feet of this well, plotted to the same scale as that of a number of sections of the Lahontan sediments measured by Antevs.[6] These sections, which are selected at random, give a correct representation of the sediments exposed in the canyons of the Truckee, Humboldt, and Walker rivers. They are numbered here as in the original paper. The heavy lines across the sections represent the base of the lake beds as determined by Antevs. In most of the sections this base is indicated by a layer of reworked gravel that lies on top of the alluvial fans on which the lake beds were deposited.

Three stages of the lake are indicated in sections 9, 13, and 16, which were measured in areas in the vicinity of the Carson Sink and less than 200 feet above it. The other sections, which were measured at higher elevations, in the valleys of the Humboldt and Walker rivers, show but two stages. The varved clays indicate that none of the individual stages endured longer than 200 years. The close correspondence of the sections with the three clay beds in the upper 77 feet of the well indicates that these beds include the entire series of Lahontan sediments.

In the complete log of the well, shown on a smaller scale at A, there are 24 other clay beds, which are described in terms identical with those used in the description of the upper three beds. Further, the log of a well drilled 15 miles south of the Timberlake well shows a total of 42 clay beds in 2,735 feet, the logs of the two wells agreeing fairly closely over the first 900 feet they have in common. If these similar clay beds represent lacustrine stages, Lake Lahontan represented only the last three stages of a long series of lakes that have waxed and waned in the Great Basin.

Hints of the existence of pre-Lahontan lakes are seen in fragments of thinolite tufa lying 100 feet above the highest level of Lahontan and 500 feet above the upper limit of this type of Lahontan tufa; in higher tilted beaches in the Walker Lake basin; and in the greater age of Great Salt Lake.

If Lake Lahontan is to be correlated with the Pleistocene glaciation because it had three cycles, with what shall the many older lakes in this region be correlated? In western Nevada the sediments of Pliocene and earlier Tertiary age are thick characteristic beds of lava, tuff, ash, tuffaceous sands, lignite, and diatomaceous earth that would have been recognized in well drillings. The Tertiary beds are greatly disturbed; they are folded, faulted, and tilted. The beds encountered in the wells are horizontal, undisturbed, unconsolidated clay and sand 2,000 to 3,000

[6] Ernst Antevs: On the Pleistocene history of the Great Basin. Carnegie Institution, Pub. 352, 1925, pp. 79, 80, 82, 85, 86, and 90.

feet thick. These later beds clearly appear to be of Pleistocene age. Some of the older Pleistocene lakes were undoubtedly contemporaneous with the glacial stages, as is suggested by the large increase in thickness in the lower beds encountered by the deeper well, but the beds alone afford no means by which a line can be drawn between Pleistocene and Recent deposits.

What becomes of the Salt when a desert Lake is desiccated?

The lower parts of the desiccated valleys of the Lahontan Basin are playas covered with silt and clay. Some of these playas have thin crusts of salt or their surface muds are saline. Analyses of the salt shows that it is nearly pure sodium chloride.

In 1911 drilling in the Great Basin was begun in search of potash, supposed to occur in bodies of buried salts, as postulated by Russell. Hundreds of wells were drilled, most of them less than a hundred feet deep, though several were carried to depths of 1,000 to 1,500 feet. These wells showed that the salts are confined to the upper beds, the lower beds not being saline. The potash salts were found to be adsorbed by the muds immediately below the surface and could not be recovered economically.

The alluvial aprons and fans in the valleys of the Great Basin slope at a gradually decreasing grade to the playas. A considerable part of the water of the streams and rainfall sinks into the alluvium. The underground water flows to the playas, where it stagnates and evaporates through the pores of the silt and the clay. As has been shown by Meinzer,[7] a large quantity of water is evaporated from the playas. The water table is close to the surface under the playas, and it rises toward the mountains with a slope somewhat less steep than that of the land. The water under the playas is brackish, but that under the slopes is fresh. The underground flow redissolves the salt beds formed in a desiccated lake and covered by clay and silt washed down from the surrounding slopes and redeposits the salt close to the surface.

As the salts travel upward through the silt and clay, they are segregated by base exchange. Among others, Gedroix[8] has done fundamental work in explanation of this phenomenon. He finds that adsorption in the soil is accomplished almost exclusively by the soil colloids and depends on the composition and concentration of the soil solution and the replaceable bases already adsorbed by the soil. Calcium is the most

[7] O. E. Meinzer: U. S. Geological Survey Water-Supply Paper 423, 1917, pp. 92-104.

[8] Unfortunately, the original work of Gedroix is published in the Russian language. A translation has been made by S. A. Waksman for the U. S. Department of Agriculture and a mimeographed copy of the translation can be found at many of the State agricultural experiment stations.

strongly adsorbed of the common bases and is followed by magnesium, potassium, and sodium in the order named. The acid radicles are adsorbed slightly or not at all unless insoluble compounds, such as calcium carbonate, are formed. Chlorine is adsorbed least of all, as the chlorides are all soluble. The action is reversible if a weaker base is present in sufficient concentration to overcome a stronger base present in small amount. As the normal soil solution is dilute, the proportions of replaceable bases in most soils is 75 to 90 per cent calcium, 10 to 15 per cent magnesium, and small percentages of potassium and sodium. In the playas the sodium is found at or near the surface; the potassium lies immediately below, adsorbed by the clays; and at greater depths magnesium and calcium predominate.

In a relatively short time after a lake has been completely desiccated, almost the only salt available for a re-solution by a succeeding lake is sodium chloride. If any considerable quantity of this salt is dissolved, the ratios of the ions will differ notably from the ratios of the ions of the rivers feeding the lakes. Table 1 shows the ratios calculated[9] for some lakes and rivers existing in the Great Basin.

TABLE 1.—*Ratio of Ions in the Water of certain Lakes and Rivers*

	K : Na	SO_4 : Cl	Na : Cl	CO_2 : Cl	Salinity (per cent)
Pyramid Lake	1 :15.97	1 : 7.82	1 : 1.21	1 : 2.88	0.3486
Winnemucca Lake	18.93	12.72	1.36	6.04	.3602
Truckee River	2.21	0.59	0.64	0.23	.0153
Walker Lake	Trace	1.11	0.74	1.37	.2500
Walker River	.....	0.46	0.60	0.25	.0180
Mono Lake	20.51	1.81	.063	1.00	5.1170
Salt, Dixie Valley	323.00	45.70	1.51	84.30	.....
Great Salt Lake	19.98	8.31	1.67	616.00	20.3500
Cottonwood Creek	3.48	0.23	0.47	0.09	.0122

The greatest contrast appears between the rivers and the salt of Dixie Valley, a typical deposit of a desiccated lake that has been modified through base exchange. The table shows that Great Salt Lake has redissolved a large quantity of salt, and that Winnemucca and Pyramid lakes have taken some salt into solution. The close correspondence of the ratios of Walker and Mono lakes with those of the rivers indicates that these lakes have not inherited any salt from an earlier desiccated

[9] Data chiefly from F. W. Clarke: U. S. Geological Survey Bull. 770. 1924.

lake. In other words, neither of the lakes last named has ever been desiccated since it was first formed.

The Testimony of Walker Lake

Walker Lake occupies a simple basin, from which there has been no overflow nor loss of salts by desiccation. It became a part of Lake Lahontan when that lake reached its highest level. A comparison of its annual increment of chlorine with its present content of chlorine should indicate the maximum time that has elapsed since it was first formed. Such a comparison shows that its age is about 1,100 years. A determination based on the rate of evaporation indicates an age of 800 to 900 years. The uncertainty in this determination is due to the variation in the area of the water surface of the lake.

Certain Pleistocene mammals lived and died in the basin of Walker Lake after it had become a part of Lake Lahontan. In addition to bones of the horse, camel, and elephant, reported by Russell as occurring in the lake beds at the head of the basin, the bones of a *Camelops* were recently found embedded in the tufa attached to the precipitous western shore of the lake about 100 feet above its present surface. The body must evidently have floated in the lake and lodged against the growing tufa, which eventually surrounded the bones.

A skull of Camelops recently described by Romer[10] still retained some muscle of the skull, and Romer therefore thinks that only a few hundred years have elapsed since the animal perished. The faunas of some other lakes, such as Fossil, Christmas, and Bonneville, are considered to be early Pleistocene, because they include *Camelops* and other forms that became extinct in the Middle West during the earlier stages of glaciation. The very recent appearance of the shore features of these lakes and the occasional discovery of evidence that men lived in this region while the lakes were in existence has led to a consideration of the possibility that this fauna survived in the Great Basin until recent time.

At Walker Lake, a remnant of Lake Lahontan, there is definite evidence that this fauna was in existence during the later stages of Lake Lahontan, and Walker Lake appears to have begun its existence not over 1,000 years ago. As all the physical and chemical evidence points to the survival of certain forms of a Pleistocene fauna in the Great Basin, it is more reasonable to think that they did survive than to ignore the evidence and insist that they became extinct simultaneously throughout North America.

[10] Alfred S. Romer: A "fossil" camel recently living in Utah. Science, n. s., vol. 68, 1928, pp. 19-20.

Age of Lake Lahontan

The assignment of Lake Lahontan to Pleistocene time by former students of this problem is based on three assumptions: (1) That the three stages of Lake Lahontan represent the only Pleistocene lacustrine periods in the Great Basin; (2) that Lake Lahontan was so saline that the present lakes can not be remnants of it; (3) that certain members of the Pleistocene fauna could not have survived in the Great Basin beyond the close of tne Glacial Period.

It has been shown that Lake Lahontan represented only the last three stages of a long series of lakes that existed in Nevada in Pleistocene time; that the assumption that Lake Lahontan was strongly saline was based on an erroneous conception of the mode of origin of the tufas, for all the biological evidence indicates that it was a fresh-water lake; that the members of the Pleistocene fauna found in the Lahontan sediments were living, since Walker Lake was formed not more than 1,000 years ago. In consideration of the data presented here and elsewhere,[11] we must conclude that Lake Lahontan existed in historic time and can be correlated more closely with the Sequoia curve than with the stages of continental glaciation.

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[11] J C. Jones: The geological history of Lake Lahontan. Carnegie Institution, Pub. 352, 1925, pp. 1-50.

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NEW INTERPRETATION OF THE PERMO-CARBONIFEROUS VARVES AT SQUANTUM[1]

BY ROBERT W. SAYLES

(Presented before Section E, American Association for the Advancement of Science, December 26, 1928)

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INTRODUCTION

An examination of thick varves in slate in a quarry on Foster Street, Brighton, Massachusetts, in 1925, indicated an interpretation of the seasons which differs materially from that made by the writer in 1915. Inasmuch as the interpretation first given [1] [2] was based on varves that stand 50 feet or more above the tillite at Squantum and that were compared directly with Pleistocene varves of the Connecticut Valley, it will be necessary first to describe the structure of Pleistocene varves in order that the different structure recently determined in the Squantum varves may be more thoroughly understood.

SEQUENCE OF DEPOSITION BY GLACIERS

As a stream comes from a glacier in summer it deposits first coarse gravel, and next, farther away, sand and finer material.[3] The thickest deposit would be near the place where the stream emerged from the glacier, and the deposit of a year might be composed of gravel only. Farther away from the ice the deposit would be a layer of sand or silt, and still farther away a layer of clay. Any sand deposited on the

[1] Manuscript received by the Secretary of the Society December 29, 1928.

gravel close to the ice in winter might be washed away during the following summer, and thus a full year's record might not be preserved so near the ice. Slightly farther away, or at the same place if the ice retreated, the record of the year would be a layer of gravel and a layer of sand, the deposits of summer and winter respectively. Still farther away the summer component of the varve would be a number of layers of sand and silt, and the winter component would be made up of clay, most of it laid down because the streams coming from the ice had frozen, and perhaps of a few thin layers of silt or possibly of fine sand. The greatest number of alternating layers in the summer component would be found at a point that varied in distance from the ice-front with depth of water and strength of stream-flow—a point where the greatest amount of sediment would come to rest and not be removed by subsequent swifter currents. Even day and night deposition due to thawing and freezing might be preserved at this optimum place. At points nearer the ice than this place the currents would be too rapid to permit the preservation of alternating summer layers, and at points farther away the sediment would not be sufficient in amount to leave a record.

Confirmatory Evidence

A study of the varve structure in the Connecticut Valley by the writer would seem to uphold the foregoing theoretical conclusions.[3] It has been found that the thickest varves and the thinnest varves have the fewest alternations in their summer components, and at the critical point mentioned above the alernating thin varves in the summer components are most numerous. For example, the Pleistocene varves studied near Hanover, New Hampshire, give the following results: Varves with summer components between 1 and 2 inches thick have, on the average, about 4 alternations in the summer components; those between 2 and 3 inches thick have 5 or 6 alternations; those between 3 and 4 inches have 9 alternations; those between 5 and 6 inches have 13 alternations, and those between 6 and 10 inches have 20 or more. At this locality varves about a foot thick appear to have the greatest number of small alternations of coarse and fine silt in their summer components. In varves having a thickness of more than a foot the alternations appear to diminish again, so that varves deposited when the ice was fairly near, having a thickness of 3 or 4 feet, may have only 1 or 2 alternations. On the other hand, varves that are very thin—a quarter of an inch or less—may contain just a thin layer of clay, and the summer component may

consist only of 1 or 2 layers of silt. Such a sequence is what would be expected in a moving ice-sheet, and at Mint Brook, near Hanover, New Hampshire, such a record can be read plainly, even though the number of years recorded there is small as compared with those recorded at some other deposits where more varves have been deposited. It is obvious that, with differing conditions of depth and stream-flow, the figures given above would vary. These recorded facts do not indicate a stagnant ice-sheet, as has recently been advocated by Flint,[4] but an actual retreating ice-sheet registering its movement in the variations of the varves deposited.

The winter components studied at Mint Brook were of interest in showing, in the lower varves, intercalations of fine sand or silt, indicating occasional thaws in winter. At places higher up in the formation, representing times when the ice was farther away, these layers are not seen, and generally it may be said that winter thaws are not recorded in the clay varves when the ice had retreated for some distance, except perhaps at the top of the winter component, where spring thaws and freezes are sometimes recorded. It is thus seen that the actual retreat of the ice is shown not only in the summer components of the banding, but in the winter components also.

The Pleistocene varves studied by De Geer, Antevs, Sauramo, and others [5] consist of a series of layers of varying texture, a foot or more thick, near the till, which show many alternations at a certain point and which diminish in both directions away from this point; and this series constitutes the summer component of the varve. The winter component consists mostly of clay containing a few layers of sand or silt, intercalated near the ice, but few if any intercalated layers of sand or silt at places higher up in the deposit, representing times when the ice had retreated some distance from the locality.[6]

Evidence presented by Varves of Squantum

With this introduction in mind, let us turn to the facts displayed by the varves at Squantum and at other places near Boston, where such slate occurs.[7] In the quarry on Foster Street, Brighton, an examination of the varves in the slate indicated that the winter components of the banding are not unbroken deposits of fine material, such as are seen in the Pleistocene varves, but are divided into a number of alternating layers of fine sand or silt. The summer deposit is composed of one or two layers of sand that is much coarser than the material of the alternating series. The same features are seen at Squantum as at

Foster Street, and they are especially well displayed in the slate at the most southerly exposure on the Squantum Peninsula, called "Squantum Southeast" in the writer's paper on the Squantum tillite.[6] When the slate in any of the exposures above the tillite in the Boston region is studied with this point in mind, it will be seen that the same rule holds true. Above the tillite at Squantum Southeast come the transition beds—first, conglomerate alternating with sandstone; then sandstone, the summer component, alternating with groups of layers of sand and clay or silt, the winter component. Usually it may be said that the summer components of the banding consist of a layer of coarse or fine sand and usually an overlying layer of fine material, indicating great slackening of stream-flow; and this couple constitutes the summer component of the banding. Above this couple is the winter component, consisting of alternating layers of silt and clay, but including occasionally a sandy layer.

Fifty feet or so above the tillite, stratigraphically, the varves are usually represented by the sandy layer of the summer component, but they are sometimes not so represented, and the results of the summer melting are found only in the layer of fine material which is always found on the coarse sandy layer where that is present. The absence of the sandy layer is due to the fact that the currents were not strong enough to carry the sand at that time and place. It is true, however, that somewhat coarser material is often found where the sandy layer should be. In a former paper, published in 1919, the persistence of this sandy layer was noted, but its true significance had not then been interpreted and its presence was explained in other ways.[7] Its correct interpretation, the writer believes, has now been given. Further study may reveal more interesting facts in connection with these varves at Squantum.

Evidence presented by other Geologists

A report of the findings presented in this paper was transmitted to Antevs and published in brief in the Annual Report of the National Research Council, Committee on Sedimentation, in 1927. In the same year Wallace published a paper in which he described the broken nature of the winter components in the slate associated with the Cobalt tillite.[9] He did not note the sandy layer nor the double nature of the summer component. The writer has a specimen of the Cobalt slate in which the sandy layer is overlain by fine material, and then by the alternating coarse and fine layers of the winter component. A specimen of slate associated with

the Cambrian tillite of Australia, sent to the writer many years ago by Dr. Howchin, also shows a broken winter component. Several years ago the writer received a collection of banded kaolinite slate from Dr. E. J. Wayland, Director of the Geological Survey of Uganda, Africa, for examination. This slate, which Dr. Wayland states is associated with a tillite, shows the same features as the Squantum slate. Its age is pre-Cambrian. Photographs of other ancient glacial slates appear to show the same features, but no reliance can be placed on photographs alone. Until the varved slates from other parts of the world are studied with this point in mind, it will not be possible to say how common this type of varve is in ancient glacial slates. The present indications are that this type may be more common than that usually found in the Pleistocene varves so far studied.

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FIGURE 1.—*Varves in Vermont*

The thick varves show the thick summer component, with many alternating layers, and the thin winter clay layer or component. View taken about 40 feet above till. Varves below are thicker than these shown. Note thinning of varves upward, due to ice recession. The locality is across river from Hanover, New Hampshire, in Vermont. Photograph by author.

FIGURE 2.—*Transition Beds*

Transition beds between tillite and slate. Conglomerate and sandstone beds. A is a conglomerate bed lying on tillite to the left. B is a bed of sandstone. Squantum Southeast. Photograph by author.

VARVES IN VERMONT AND TRANSITION BEDS

FIGURE 1.—*Coarse sandy Summer Components and alternating Winter Components of finer material. A—Summer. B—Winter.*

The locality is Squantum Southeast. Photograph by author.

FIGURE 2.—*Sandy Summer Components showing in light color and dark Winter Components*

The fresh fracture on the right shows the banding, which does not appear on the left on account of weathering and vegetal growth. This view was taken about 20 feet stratigraphically above plate B, figure 1. Squantum Southeast. Photograph by author.

FIGURE 1.—*Coarse sandy Summer Components and alternating Winter Components of finer material*

Locality is Foster Street, Brighton. X 2. Photograph by E. C. Jeffrey.

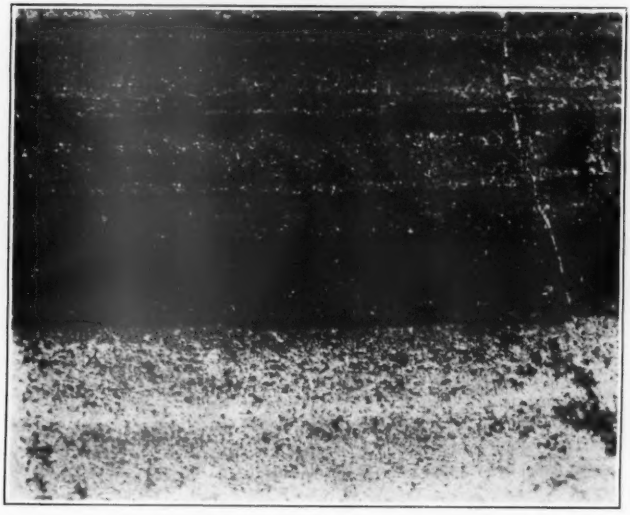


FIGURE 2.—*Coarse Summer Component with fine material lying on it, followed by alternating layers of Winter Component*

The locality is Squantum Head. X 10. Photograph by E. C. Jeffrey.

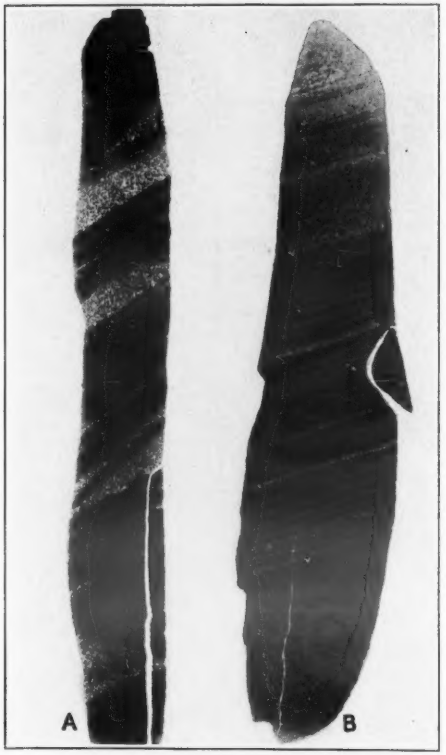


FIGURE 1.—*Summer and Winter Components*

A. At left. Summer and winter components. Squantum Southeast. X 1. Photograph by E. C. Jeffrey.

B. At right. Coarse summer components and alternating winter components of finer material. Squantum Head. X 2. Photograph by E. C. Jeffrey.

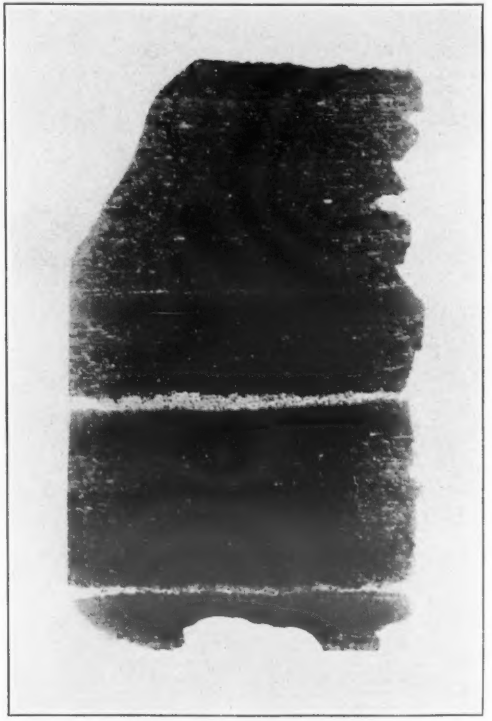
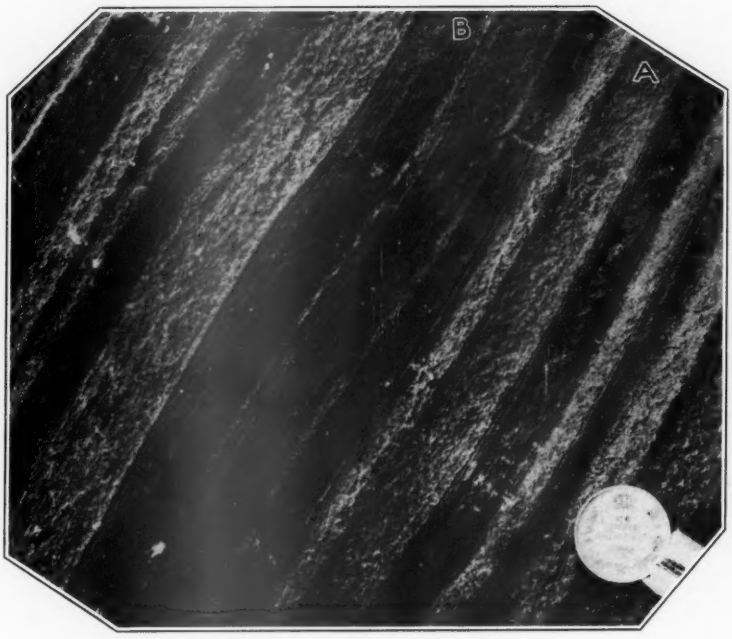


FIGURE 2.—*Summer Component and alternating Winter Component*

The sandy layer with fine material above comprising the summer component and the alternating winter component. Squantum Head. Photograph by author.



HURONIAN SLATE NEAR TILLITE

A close view of Huronian slate near tillite, showing coarse sandy layer and alternating layers of fine sediment.

A. Sandy summer components.

B. Alternating winter components.

Cobalt, Ontario. Photograph by A. C. Swinnerton.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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KEEWATIN-TIMISKAMING BOUNDARY*

BY E. S. MOORE

(Read before the Society December 29, 1928)

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INTRODUCTION

In a recent article Gregory and Barrett[1] state that the Keewatin and Timiskaming are approximately or completely contemporaneous. They further state that their contention is supported by the order of the pre-Paleozoic succession in Scotland as well as by that in several areas in Canada. Probably without fully appreciating the magnitude of the problems confronting the worker in the Canadian Shield, where the formations are so highly metamorphosed, and the Keewatin-Timiskaming areas, that have been studied in detail, are so widely separated from one another without connecting links, these writers give somewhat the impression that the Canadian classification of the older pre-Cambrian rocks is in a state of confusion.

In some areas in the Canadian Shield there is difficulty in distinguishing volcanic rocks which are more or less common to these two series or systems, but in most areas there is a fairly distinct break between them. This break is as prominent as that between many of the systems

* Manuscript received by the Secretary of the Society January 4, 1929.

[1] J. W. Gregory and B. H. Barrett: The stratigraphical position of the Keewatin. Jour. Geol., vol. 35, 1927, p. 141.

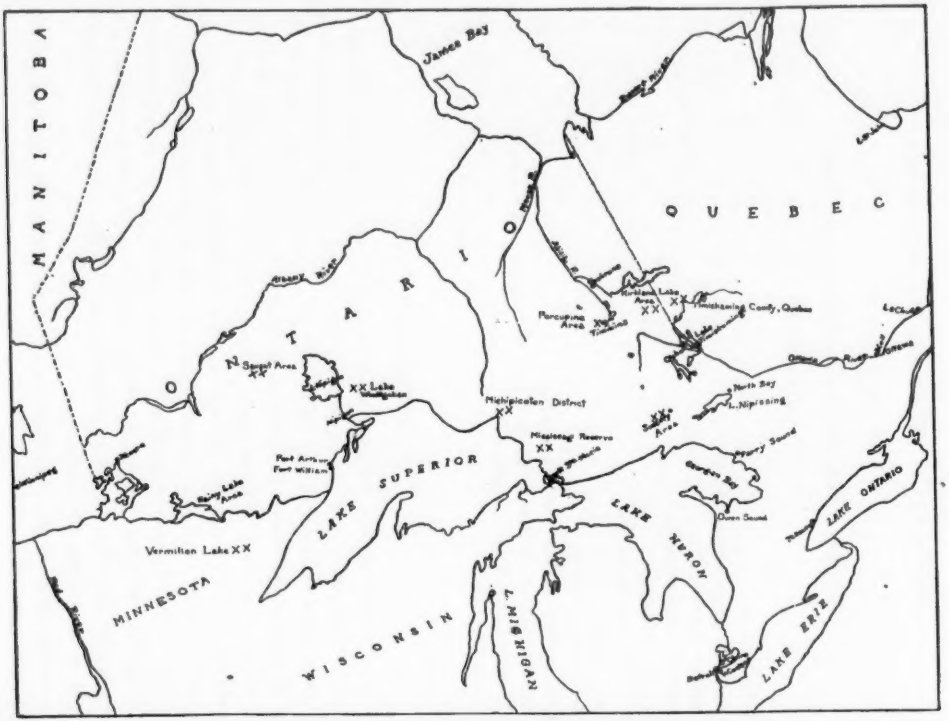


FIGURE 1.—*Sketch Map showing the Location of Keewatin-Timiskaming Areas*

in later groups of formations and at some places is much more prominent. Much of the difficulty in correlation is due to the necessity of correlating formations on lithological grounds only, because fossils are lacking and the metamorphism of the rocks makes it almost impossible at some places, even in the same basin, to determine the succession of the series. In their attempts at correlation, Gregory and Barrett emphasize the relative amount of mechanical metamorphism suffered by the Keewatin and Timiskaming series; but difference in metamorphism is not a safe foundation on which to build a classification, as is known by every geologist who has worked in the Canadian Shield. In many areas where there is no doubt as to the succession, the younger, dominantly sedimentary series is much more metamorphosed mechanically than the older, dominantly igneous series. In the broader parts of synclines the pillow lavas of the Keewatin may be only slightly schistose, but if these rocks are followed to the narrower, more closely compressed sections of the same structures, they will be found mashed into schists. The Timiskaming sediments and the few lava flows interbedded with them seem to yield more readily to squeezing than the large areas of Keewatin lavas and coarse-grained intrusives.

The writer recognizes that some of the series that have been placed in the Timiskaming have not been classified as Timiskaming by all Canadian geologists. Some series have been so classified for many years and are cited as indicating a distinct break between the Keewatin and Timiskaming. Others are included in the Timiskaming, which, in the light of studies of the shield as a whole, seem to fall readily into the scope of this discussion. Some of those concerning which the writer was doubtful a few years ago, while he was mapping them, seem on further study to be susceptible of classification into Keewatin and Timiskaming series or systems, such, for example, as the Batchawana series and the Savant group. In mapping them local names were applied, to be used until more general terms could be employed with greater certainty.

Original Timiskaming Section

The name Timiskaming was first applied by Miller [2] to a series of sediments around Lake Timiskaming (formerly Lake Temiscamang), on the Ontario-Quebec boundary. The series had been described by Logan [3] many years before and was regarded as Huronian. It consists, in addition to quartzite, of a slate-conglomerate overlying granite

[2] W. G. Miller: Eng. and Min. Jour., 1911, p. 648.
[3] Sir William Logan: Geology of Canada, 1863, p. 50.

gneiss and containing boulders of the gneiss up to a foot in diameter, as well as pebbles of dark-green feldspathic rock. The associated hard, siliceous slate is striped in bands of different colors. This distinct banding is a striking feature of the Timiskaming series in some other areas. It is so regular as to strongly resemble varves. These banded slates grade into cherts in some areas, and although there was a distinct original banding in the sediments it has been emphasized by silicification and replacement. The banding resembling varves in these sediments, coupled with the presence of large boulders in graywacke of the Timiskaming series in the Kirkland Lake area, has led Coleman to suggest a glacial origin for at least part of this series. The series is highly tilted and it includes no igneous rocks. Above the slate and conglomerate in Logan's section there is a thick quartzite.

On Kirk and Cross lakes, on the border of the Cobalt district, in the same region as Lake Timiskaming, Miller found a much disturbed conglomerate series overlying the Keewatin. He regarded this series as equivalent to the type section of the Timiskaming. The Keewatin consists of greenstone, schist, quartz porphyry, rhyolite, chert, and banded iron formation, and fragments of all these rocks are found in the overlying conglomerate, as well as pebbles and boulders of granite and syenite. Miller states that there is a recognizable unconformity between the Keewatin and the Timiskaming. The Timiskaming is intruded by the Algoman granite, which is overlain by the Cobalt series.

Sudbury Series

In 1913 Coleman [4] applied the term Sudbury series to formations lying south and southwest of the Sudbury nickel basin and that are about 30,000 feet thick. This series includes much igneous rock, some of which is undoubtedly contemporaneous with part of the sediments. The sediments comprise slate, graywacke, arkose, quartzite, and bands of conglomerate containing pebbles and boulders of granite. They are highly squeezed and have been so greatly metamorphosed that parts of the arkose and quartzite can be distinguished with difficulty in the field from felsite. The area contains no granite that is regarded as equivalent in age to the boulders in the conglomerate. This series is generally regarded as Timiskaming in age, and it has been separated from the Keewatin greenstones in mapping the area. The Mississagi quartzite of the Bruce series (Lower Huronian) immediately overlies it.

[4] A. P. Coleman: The nickel industry, with special reference to the Sudbury region. Canada Dept. of Mines, Mines Branch, 1913, p. 6.

Ogishke Conglomerate

Turning westward to the Vermilion district of Minnesota, we find the Ogishke conglomerate, which was described by Van Hise and Leith [5] as ranging from a great formation in some places to one that is almost absent in others. It was regarded as Lower Middle Huronian, but Cooke [6] and other geologists, for apparently good reasons, have assigned this formation to the Timiskaming rather than to the Huronian. It is closely infolded in the underlying Keewatin formations, but there is an important unconformity at its base. The conglomerate contains pebbles and boulders of the underlying greenstone, chert, and jasper as well as of the Laurentian granite exposed in the area.

Cooke also places in the Timiskaming Lawson's Steeprock and Seine series of the Rainy Lake area, and these also contain fragments of the Laurentian granite. There is a distinct unconformity between them and the Keewatin.

Savant Group

In the Lake Savant area, 140 miles northwest of Lake Superior, there is a very thick series of sediments, which the writer formerly regarded as Huronian.[7] During recent work in this area a great conglomerate, more than 1,000 feet thick in some places, but varying rapidly in thickness from place to place, was traced without break for more than 55 miles. Were it not for this conglomerate it would be difficult to separate the dominantly igneous Keewatin series below from the overlying, dominantly sedimentary series, regarded as Timiskaming. The igneous activity of the earlier period continued, although much abated, into the later period, and pillow lavas, rhyolites, agglomerates, and tuffs are interbedded with the sediments of the Timiskaming. These later lavas are, on the whole, much more acid than those mapped as Keewatin. Greenstone and diorite of uncertain age intrude at least part of the Timiskaming sediments.

The Timiskaming sediments comprise conglomerate, arkose, graywacke, slate, a little quartzite, and the main iron formation of the area. The conglomerate contains pebbles and boulders of all the Keewatin rocks and large boulders of granite and granite gneiss, some as

[5] C. R. Van Hise and C. K. Leith: Geology of the Lake Superior region. U. S. Geol. Survey, Mon. 52, 1911, p. 129.

[6] H. C. Cooke: "Between the Archaean and the Keweenawan is the Huronian." Roy. Soc. Canada, 3d ser., vol. 20, sec. iv, 1926.

[7] E. S. Moore: Lake Savant Iron Range area. Ont. Bur. Mines, vol. 19, pt. 1, 1910, p. 173.

much as 45 inches in diameter. Most of these boulders are well rounded. No granite that could have supplied these fragments has been certainly recognized in the area. The finer-grained sediments are in many places highly banded, as they are in the type section of the Timiskaming series. These rocks are intruded by batholiths of granite, which are believed to be Algoman. The granite is the latest pre-Cambrian rock in the area except a few diabase dikes, which are regarded as Keweenawan.

The Keewatin of this area consists chiefly of basic to intermediate lavas, most of which show ellipsoidal structure. There are a few rhyolite flows and some local bands of jasper iron formation and conglomerate, but all the pebbles in the conglomerate are of local origin. The pillow lavas are highly tilted, but at many places they have undergone very little dynamic metamorphism compared with the overlying Timiskaming series.

Batchawana Series

The Batchawana series occurs on the upper waters of the Batchawana River, in the Mississagi Forest Reserve, about 75 miles north of Sault Sainte Marie, Ontario.[8] This area lies between the Sudbury area, described above, and the Michipicoten area, to be mentioned later. It includes an important conglomerate containing pebbles and boulders of granite not found in place, as well as those of greenstone, schist, rhyolite, quartz, and jasper, derived from the underlying formations. There is a gradation from rhyolite through rhyolite-agglomerate or breccia to the overlying conglomerate. The sediments overlying the conglomerate are arkose, graywacke, tuff, quartzite, banded, siliceous iron formation, paragneiss, and a little interbedded lava. In some areas the sediments are distinctly banded almost as well banded as iron formation. This series is greatly squeezed and tilted and is intruded by Algoman granite, which in turn is cut by Keweenawan diabase dikes.

Doré Series

The term Doré series was applied by Logan[9] to certain sedimentary rocks outcropping at the mouth of the Doré River, in the Michipicoten district. The series, as later described by Collins and Quirke,[10] consists of conglomerate, graywacke, and stratified pyroclastic material.

[8] E. S. Moore: Mississagi Reserve and Goulais River iron ranges, District of Algoma. Ont. Dept. Mines, vol. 34, pt. iv, 1925, p. 5.

[9] Sir William Logan: Geology of Canada, 1863.

[10] W. H. Collins, T. T. Quirke, and Ellis Thomson: Michipicoten iron ranges. Canada Geol. Survey. Mem. 147, 1926, p. 12.

It is highly folded. The conglomerate contains pebbles and boulders of granite (the largest 30 inches in diameter), as well as those of schist, porphyry, felsite, and breccia derived from the underlying formations.

Coleman and Willmott [11] regarded this series as Upper Huronian, but Collins and Quirke place it in the Keewatin, between two volcanic series. They find also a gradation from underlying lavas and tuffs upward into the conglomerate, such as is seen in the Batchawana series. There seems to be a striking similarity, however, between the Michipicoten section and that in the Mississagi Reserve on one hand and that in the Lake Savant area on the other. There is the same evidence of the continuance of volcanic activity and the deposition of banded iron formation above the main conglomerate in all these areas, although the vulcanism is much less evident in the Mississagi area than in the other two.

Collins and Quirke [12] speak of the unconformity beneath the Doré series and of a pre-Dorean granite of Keewatin age. This rock is described as the oldest granite yet found in the Canadian Shield. There is no good reason for assuming that granites older than Laurentian could not exist; but, until we have more evidence of the greater age of this particular granite, there seems much in favor of regarding it as Laurentian. If there is a sufficiently large break at the base of the Doré series to permit this plutonic rock to be uncovered and eroded to supply the boulders to the conglomerate, it would appear that the Doré series might be raised from the Keewatin to the Timiskaming. Granite batholiths intrude all these formations.

Windegokan Series

Tanton [13] has applied the term Windegokan series to a highly folded conglomerate found east of Lake Nipigon, Ontario. This conglomerate was described by the writer [14] in 1907, and, in keeping with the custom of that time, it was classified as basal Huronian. It should probably be lowered to the Timiskaming horizon. It contains well-rounded boulders and pebbles of granite, as well as those of the underlying schist, greenstone, and iron formation, although no granite of the age of the boulders has been found in place in the area. No igneous rocks occur

[11] A. P. Coleman and A. B. Willmott: The Michipicoten iron region. Ont. Bur. of Mines, Ann. Rept. 1902, p. 155.

[12] Op. cit., p. 26.

[13] T. L. Tanton: Canadian Northern Railway between Nipigon and Longeulac, northern Ontario. Canada Geol. Survey, Summ. Rept., 1917, Pt. E.

[14] E. S. Moore: The iron ranges around Lake Windegokan. Ont. Bur. Mines, 16th Ann. Rept., 1907, p. 136.

in the Windegokan series. It is intruded by granite batholiths believed to be Algoman.

Timiskaming of the Porcupine Area

The Timiskaming in the Porcupine area consists, according to Burrows,[15] of a conglomerate which is overlain by graywacke and slate which have a well-marked banded structure. It contains pebbles of granite, felsite, porphyry, quartz, and iron formation. It overlies unconformably the Keewatin, which comprises pillow lava, rhyolite, volcanic breccia, iron formation, slate, and schist. Burrows states that the unconformity between the Timiskaming and Keewatin is well marked by the folding and erosion of the Keewatin, as well as by the presence of granite boulders brought from other areas to the basal conglomerate of the upper series. In spite of its lesser age, the Timiskaming is at many places more metamorphosed than the Keewatin. There is no igneous rock in the Timiskaming series, but it is intruded by quartz porphyry and granite batholiths of the Algoman.

Timiskaming of Kirkland, Larder, and Kenogami Lake Areas

In the Kirkland Lake area the Timiskaming has been studied by several geologists. Burrows and Hopkins[16] describe this series as a narrow band of sediments extending east-west for about a hundred miles. The rocks are conglomerate, graywacke, slate, quartzite, and tuff. The tuff has been recognized by Todd and other recent workers in the district. The chert, graywacke, and slate are almost as well banded as iron formation. The conglomerate contains pebbles of granite, porphyry, iron formation, greenstone, and lavas. It overlies the Keewatin, which is composed of greenstone, pillow lava, altered diabase, rusty carbonate and iron formation, and Burrows and Hopkins state that there is a distinct erosional unconformity between the Keewatin and Timiskaming. In places the younger series is dynamically more metamorphosed than the older.

In the region east of Kirkland Lake, on Kenogami and Round lakes, Cooke[17] has found that the Timiskaming formation consists entirely of conglomerate containing pebbles of granite and of the underlying Keewatin, which includes basalt, tuff, and iron formation. In the Larder Lake area the Timiskaming includes conglomerate, sandy gray-

[15] A. G. Burrows: The Porcupine gold area. Ont. Dept. Mines, vol. 33, pt. ii, 1924.

[16] A. G. Burrows and P. E. Hopkins: The Kirkland Lake gold area. Ont. Dept. Mines, vol. 32, pt. iv, 1923.

[17] H. C. Cooke: Kenogami, Round and Larder Lake areas, Timiskaming District, Ontario. Canada Geol. Survey, Mem. 131, 1922, p. 4.

wacke, slate, basalt, and soda trachyte. There is evidence of rather extensive volcanic activity near the close of the Timiskaming period. The conglomerate, which at some places reaches a thickness of 600 feet, contains pebbles and boulders of granite and the Keewatin formations. This series is intruded by the Algoman porphyries and granite batholiths.

Formations in Timiskaming County, Quebec

The conditions in Timiskaming County resemble in some respects those in the Michipicoten and Lake Savant areas, where there is a merging of sedimentary and igneous processes. Wilson [18] applied the names Timiskaming group and Abitibi group to all the pre-Cobalt formations except the granites because, in his opinion, the lower group does not correspond in many respects to the Lake Superior Keewatin or the upper group to the Timiskaming series elsewhere. However, the Abitibi group consists chiefly of volcanic rocks like those found elsewhere in the Keewatin. It contains, in addition, agglomerate, tuff, slate, phyllite, banded iron formation, and ferruginous dolomite. The Pontiac series is placed in the Abitibi group, although Wilson states that there is no conclusive evidence regarding its age. This series contains graywacke, arkose, much mica schist, and local bands of conglomerate containing pebbles and boulders of granite, rhyolite, quartz porphyry, and quartz. The Larder Lake series, which consists of phyllite, slate, and ferruginous dolomite containing chrome mica, is placed in the Abitibi group. The lavas of this group are at many places but little altered mechanically. The Timiskaming group, according to Wilson, includes the Kirkland Lake series, described above, and the Fabre series, which some geologists have regarded as younger than the Timiskaming.

Summary

The description of areas containing Timiskaming and Keewatin formations might be enlarged considerably, but enough has been said to show the general relations of the two series over a large area in the Canadian Shield. Although the conditions in the areas described differ considerably, there is in all a marked similarity in what may be regarded as the Timiskaming series. It is highly folded in all areas and it is characterized by a prominent basal conglomerate containing boulders and pebbles of granite, some of them large and most of them well rounded. Banding in the sediments, approaching varving, is a common and striking feature of the sediments in most of the areas studied.

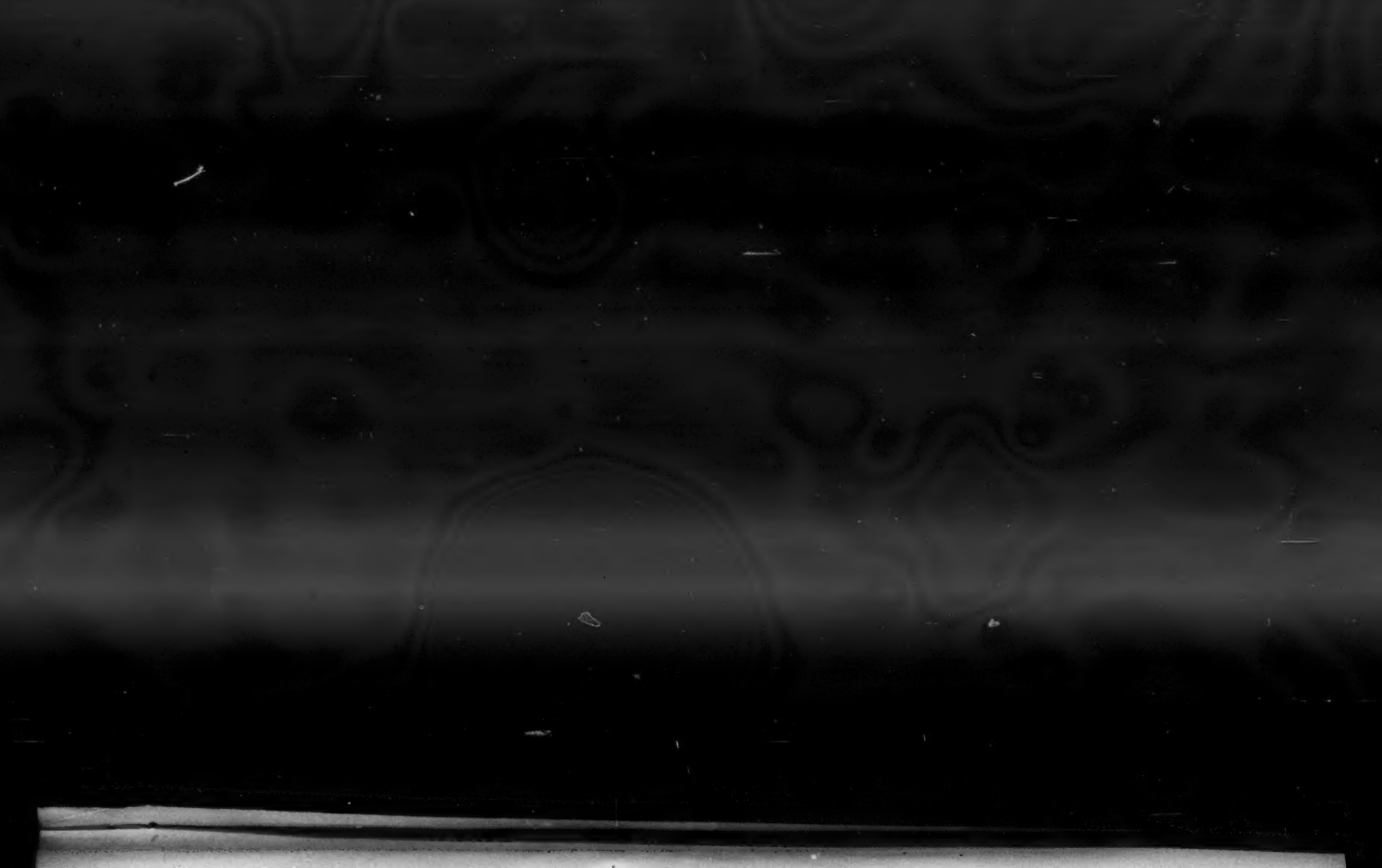
[18] M. E. Wilson: Timiskaming County, Quebec. Canada Geol. Survey, Mem. 103, 1918, p. 49.

In some areas the Timiskaming is a strictly sedimentary series, as it is in the type locality; in others the volcanic activity of the Keewatin continued, although with lesser intensity, into the later period. In some areas the basal conglomerate rests on the granite from which its boulders were derived, but in the majority of them no granite that could have supplied the boulders is found in place. In every area mentioned there are later granite batholiths, and it seems probable that these wiped out much of the older granite, for they probably rose in many places along the geanticlines that were formed when the Laurentian was injected.

In only a few of the areas considered has a nonconformity been clearly recognized, as would be expected in view of the extent to which the formations have been metamorphosed. A disconformity, however, is found everywhere between what are here regarded as the Timiskaming and the Keewatin series, and it must be of considerable magnitude, for the conglomerate contains fragments of all the underlying Keewatin rocks, as well as large boulders of granite, nearly all of which have been brought some distance from outlying areas. The unconformity is certainly as great as that which separates many systems in later groups.

The evidence now available indicates that at the beginning of the diastrophism that brought to a close the Keewatin period and ushered in the Laurentian great anticlines rose slowly in the areas adjacent to the basins in which the Timiskaming was deposited. Beneath these anticlines the Laurentian batholiths crawled upward. The tops of these batholiths, which were in time removed by erosion, furnished material for the Timiskaming conglomerate. In some areas the diastrophism was not so severe as in others, or its climax was reached somewhat later, and in these areas the volcanic activity of the Keewatin period extended into the Timiskaming. These conditions would explain the mixture of lavas and sediments in some areas. The lavas in a number of Keewatin-Timiskaming areas generally grow more acid toward the top of the Keewatin. Many of the flows and dikes of rhyolite and quartz porphyry near the top of the Keewatin and in the Timiskaming sediments may be the shallower manifestations of the Laurentian magma.

In any consideration of the Timiskaming-Keewatin unconformity it must be borne in mind that there are considerable bodies of sediment in the most typical Keewatin sections. The conglomerate pebbles are, however, of local origin and some of them probably represent water-worn agglomerates. Further, if there is much of the Timiskaming series in Canada outside of the original section, the presence of igneous rocks in it must be regarded as a common feature.



	Original Timiskaming area	Kirk and Cross Lake area	Sudbury area	Vermilion district	Rainy Lake area	Savant
Algoman, etc., batholithic intrusions	Granite	Granite	Bruce series of sediments	Granite	Granite	Granite
Timiskaming series	Folded and tilted	Highly folded	Highly metamorphosed	Highly folded	Folded and tilted	Folded and
	Banded structure		Banded structure			Banded st
	Quartzite, chert, and slate	Graywacke	Sudbury series Igneous rocks, slate, quartzite, graywacke, and arkose	Agawa Iron formation and slate	Steeprock and Seine series Sediments and volcanics	Interbedde quartzit formatio paragne
	Conglomerate, with boulders from granite and Keewatin	Conglomerate, with boulders from granite and Keewatin	Conglomerate, with boulders from granite and Keewatin	Ogishke conglomerate, with boulders from granite and Keewatin	Conglomerate, with boulders from granite and Keewatin	Conglom with b from and Ke
	Nonconformity	Nonconformity	Disconformity	Nonconformity	Nonconformity	Disconfor
Laurentian	Granite and gneiss	Not exposed	Not exposed	Granite and gneiss	Granite and gneiss	Not expos
Keewatin	Not mentioned	Greenstone, schists, quartz porphyry, rhyolite, chert, and banded iron formation	Greenstone and green schists	Pillow lavas, greenstone, schists, quartz porphyry, and iron formation	Volcanics, intrusions, agglomerates, chert, slate, limestone, and schists	Pillow lav formatio local b congolo

*Banded structure slate, chert, graywacke, and arkose of Timiskaming series.

Suggested Relations of the Series described

	Vermilion district	Rainy Lake area	Savant area	Mississagi Reserve	Michipicote
of	Granite	Granite	Granite	Granite	Granite
r-	Highly folded	Folded and tilted	Folded and tilted	Folded and tilted	Folded an
e			Banded structure	Banded structure	
s, e, d	Agawa Iron formation and slate	Steeprock and Seine series Sediments and volcanics	Interbedded lavas, quartzite, iron formation, and paragneiss	Interbedded lavas, slate, graywacke, arkose, iron formation, and paragneiss	Post – volcanic Stratified clastics series
, s e	Ogishke conglomerate, with boulders from granite and Keewatin	Conglomerate, with boulders from granite and Keewatin	Conglomerate, with boulders from granite and Keewatin	Conglomerate, with boulders from granite and Keewatin	Doré con ate, with ers from and Kee
	Nonconformity	Nonconformity	Disconformity	Disconformity	Disconform
	Granite and gneiss	Granite and gneiss	Not exposed	Not exposed	Granite an
l	Pillow lavas, greenstone, schists, quartz porphyry, and iron formation	Volcanics, intrusions, agglomerates, chert, slate, limestone, and schists	Pillow lavas, iron formation, and local bands of congolomerate	Pillow lavas, rhyolite, agglomerate, tuff, and iron formation	Pre-Dorea canics a formatio

Michipicoten district	Windegokan area	Porcupine area	Kirkland Lake, etc., area	Timiskaming County, Quebec
Granite	Granite	Granite and porphyry	Granite and porphyry	Granite
Folded and tilted	Highly folded	Folded and tilted	Folded and tilted	Folded and tilted
		Banded structure	Banded structure'	
Post – Dorean volcanics Stratified pyroclastics of Doré series		Graywacke and slate	Quartzite tuff, slate, and graywacke	Pontiac series of Abitibi group Arkose, graywacke, and mica schist
Doré conglomerate, with boulders from granite and Keewatin	Conglomerate, with boulders from granite and Keewatin	Conglomerate, with boulders from granite and Keewatin	Conglomerate, with boulders from granite and Keewatin	Conglomerate, with boulders from granite and Keewatin
Disconformity	Disconformity	Nonconformity	Disconformity	Disconformity
Granite and gneiss	Not exposed	Not exposed	Not exposed	Granite and gneiss
Pre-Dorean volcanics and iron formation	Volcanics and schist	Pillow lavas, volcanic breccia, iron formation, slate, and schists	Pillow lavas, greenstone, diabase, rusty carbonate, and iron formation	Volcanics (chiefly) agglomerate, tuff, slate, phyllite, and ferruginous dolomite

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METAMORPHIC OROGENY[1]

BY BAILEY WILLIS

(*Read before the Society December 28, 1928*)

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AVAILABLE FORCES

On examining the rocks of a mountain range the geologist is impressed by the fact that work has been done in folding, faulting, and uplifting them. Work implies force, and the investigator is led to inquire what forces are available and competent to produce the stupendous effects which the study of mountains and continents discloses.

In modern geology current thought appeals almost exclusively to gravity to answer this question. The various aspects of the Contraction theory of mountain-building invoke horizontal thrust, but attribute that thrust simply to the gravitative settling of the crust on a cooling nucleus or to the weight of heavier wedges pressing against lighter segments. Isostatic theories rest on the concept of unequal loading, it being postulated that there is a deep-seated underflow from a more heavily loaded area toward an unloaded area, and that the undertow drags the superficial crust with it. In all of the various alternative hypotheses which fall into these two general groups, gravity is the initial cause assumed to actuate the tangential movement. It has repeatedly been shown that gravity is incompetent to produce the observed effects, if the crust of the earth is as strong as observation and experiment indicate it to be. Advocates of these theories are therefore forced to imagine conditions favorable to mobility in the rigid earth. The zone of flow suggests convenient concepts, either of a more or less plastic condition or of

[1] Manuscript received by the Secretary of the Society July 8, 1929.

NOTE.—This article was written during a voyage to East Africa under conditions which made references to geologic literature impossible. It therefore lacks those citations of the work of others which it should contain.—B. W.

a glassy, liquid layer which will yield to small, persistent stresses applied during a long period.

It has long appeared to the writer that these simple assumptions of a plastic or liquid mobile layer were evasions of the issue; that they are not adequately sustained by observational data and are not consistent with either the results of experiments or the course of geologic history. A more promising line of attack on the problem of orogeny appeared to be offered by recognizing the incompetence of gravity alone and by searching for more powerful forces that would act in cooperation with it.

The search for forces leads directly to recognition of the forms of energy known through researches in physics. Gravity is a dominant and persistent force which can not be set aside. Molecular attractions and repulsions are everywhere present, but they are locked in balanced systems, which hold their enormous potencies to potential rather than dynamic conditions. Heat or molecular vibration is a fluid form of energy which may develop from the transformation of other forms, is capable of transfer from point to point, and is competent to stimulate into activity energies far greater than itself. Radioactivity is a superpower, but is not as yet sufficiently well understood to form the basis of reasonably sure postulates regarding its distribution and possible effects.

Terrestrial energy thus takes at least three forms which are available for geologic processes: gravity, molecular potencies, and heat. The first two tend to maintain stable conditions. They are conservative. Heat is by contrast the mobile form of energy and is revolutionary in its effects. It is therefore to heat that we must look to initiate any change in the structure of the earth. Once thrown out of static balance, the molecular potencies and gravity are capable of producing any of the effects of orogeny.

How are the balances disturbed? Through what mechanisms do they operate when disturbed?

Fixing attention on heat, the problem is to define the sources at which it is generated, to consider how it is transferred and concentrated, and to recognize the mechanism through which it is made effective to free molecular potencies and disturb the balance of gravity. In so complex a structure as our globe, there are probably many mechanisms through which heat operates. The present discussion is not advanced as an only or ultimate solution. Nevertheless, it appears to satisfy the known facts in a manner which justifies its being regarded as a promising working hypothesis.

The basic assumption is that orogenic movements originate in solid crystalline rocks. The crystallogenic forces locked up in the latter can be released by heat, especially in the presence of unbalanced stresses.

Their activity can be stimulated by hot vapors. These processes result in metamorphism. They lead to rearrangements of molecules in adjustment to stress environment. Crystals change their forms forcibly, shortening and elongating. They thus exert pressures that produce mountain ranges. The process is therefore appropriately described as metamorphic orogenesis.

Dynamic Spheres

It is usual to describe the globe as a sphere of matter. Rocks and their chemical constitution are the leading subjects of study and discussion. It would be quite as appropriate to describe the globe as composed of energy, from the Einstein point of view; but, without adopting the extreme hypothesis that matter is energy, we must recognize that the matter of the earth is highly charged with energy, and that the characteristics of matter depend on the kind and degree of energy with which it is charged. The difference between a magma and the crystalline rock formed from it is not one of substance, but of the energies that distinguish one state from another.

Furthermore, it is not the absolute degree of energy present, but the relative degree as between two or more forms of energy. Thus, if a rock be under pressure due to gravity and be heated, it is not the absolute pressure or the absolute temperature which determines its state, but the relation of pressure and temperature.

This point of view being assumed, we may consider the hypothetical spheres into which the globe may be divided according to the relations of heat and pressure in different parts and their effects on rocks of different compositions. Since the emphasis is on the forces rather than on the kinds of substance, the parts may be designated dynamic spheres.

We shall distinguish the core and the envelope; and the latter will be divided into an inner shell called the strong sphere or *stereosphere,* an intermediate shell called the weak sphere or *"asthenosphere,"* and the outer shell.

On the evidence accumulated and analyzed according to the principles of physics, chemical petrology, and seismology, as recently discussed by L. H. Adams, Washington, Macelwane, and others, it appears most probable that the globe contains a very hot core surrounded by a more or less heated envelope. The evidence, as I understand it, has been summarized and the literature cited. It and the arguments drawn from it need not be presented again in this place.[2] It will suffice to summarize the conclusions:

1. The earth has a core which is inelastic and is therefore probably

[2] Bailey Willis: Continental genesis. Bull. Geol. Soc. of Am., vol. 40, 1929, pp. 281-336.

superheated beyond the degree at which pressure can maintain a rigid, crystalline, elastic state. Admitting that the temperatures and pressures so greatly exceed our experience that the terms we commonly use to describe states of matter may be misleading, we can do no better than to describe the core as a nonsolid body, consisting probably of an exceedingly dense, viscous melt. The words liquid or gaseous convey notions of mobility that can not exist under the extreme pressures of the interior. Nonsolid, inelastic, superheated appear to be appropriate adjectives by which to describe the state of the core. Its diameter is about half that of the globe.

In its superheated condition the core constitutes the source of energy that justifies the concept of the globe as a heat engine. Becker has discussed the earth as such and has considered one form of action by which its forces might raise mountain chains.[3] The older views of Mellard Read need no introduction. Though the core may be regarded as the principal source of heat energy, this does not exclude consideration of other developments of high temperature, due to the transformation of work into heat, or to chemical changes, or to radioactivity, the last named being probably superficial.

2. Surrounding the core is an envelope whose thickness approximates the outer half of the earth's radius. It consists presumably of crystalline rock, presenting holocrystalline or schistose structures according to the conditions of stress to which any section may locally be subjected. The temperature in the contact zone near the core must be very near that of the core, yet enough lower to permit the elastic, crystalline state to exist. If that temperature be exceeded, the rock melts and becomes core; or, if the surface of the core be chilled below the melting point, it becomes envelope. The distinction depends on dynamic conditions, not necessarily on constitution.

From the innermost zone outward the temperature of the envelope is believed to fall off in such a manner that the solid condition is generally maintained in spite of diminishing, gravitative pressure. Gradient curves, deduced on the assumption that the globe is homogeneous or is composed of shells each of which is homogeneous within itself, may represent a general law of heat distribution; but the local conditions must depart widely from the average temperature thus inferred if the earth is heterogeneous, as is probably the case.

The generally solid state of the envelope is attributed to a dominance of pressure over temperature by a safe, though narrow, margin. A local rise of temperature over the limit up to which the local pressure can

[3] George F. Becker: The earth regarded as a heat engine. National Academy of Sciences. vol. 1, 1916, pp. 82-87, 127-130.

maintain solidity may, and probably does, from time to time occur. Strain is regarded as a cause of local melting, especially shearing strain, which, in consequence of the breaking down of molecules and the conversion of work into heat, may cause the formation of thin lenses of molten rock. Lenses of this origin would resemble dikes; but, being developed *in situ* by indigenous energy, they may be called *autogenous dikes*. The process of their formation may be called *strain-melting*. Molten lenses or masses, whatever their form, transmit pressure hydrostatically, and therefore exert in their higher portions a pressure related to that of their deeper levels and in excess of that of the solid walls. This condition, coupled with the effects of unbalanced stresses, must lead to their extrusion from deeper to higher zones. They carry their latent and sensible heat with them, and thus produce in the solid envelope somewhat the effect that convection currents do in a liquid mass.

Thus, as was pointed out by Chamberlin, heat is transmitted through the solid earth from within outward by conduction and by melting and extrusion, but irregularly. Of the two methods of transfer, conduction is the more universal, but not uniform and exceedingly slow. Melting is narrowly local in occurrence, but intense and efficient within its sphere of action in any particular occurrence.

3. It is postulated that a greater resistance to melting distinguishes an inner shell of the envelope from an outer. The inner dynamic shell, which may be regarded as extending to two-thirds of the total thickness of the envelope, is thought to be characterized by a decided dominance of pressure over heat in controlling the state of matter, excluding the zone immediately surrounding the superheated core. In general, therefore, a significant rise of temperature adequate to cause melting requires a pronounced change of the dynamic conditions. The shell in general remains solid. It is very strong, elastic, and rigid and may be called the strong shell or sphere, or the *stereosphere*.

The stereosphere is regarded as having a thickness of 1,200 to 1,500 miles. Its upper limit is indefinite, being dependent on a closer approach to equilibrium between the opposed effects of pressure and temperature, so that a smaller increment of energy is required to produce melting at superior levels. Lunn's curve for the temperature gradient in a solid globe [4] shows that this would normally be the case in a homogeneous sphere on the basis of conduction alone. This effect would be augmented in a heterogeneous shell, especially where layers of acid rock had become differentiated from more basic facies, as is more likely to have

[4] T. C. Chamberlin and R. D. Salisbury: Manual of Geology, 1909.

been a common occurrence in a higher than in a deeper part of the envelope.

4. That portion of the envelope which lies outside of the stereosphere and which is distinguished from it by conditions more favorable to melting was first described by Barrell and by him was called the sphere of weakness, or the *asthenosphere*. It is desirable to point out that "weakness" in this connection does not mean lack of solidity or rigidity. The term describes a dynamic condition that is not unfavorable to melting and to the local weakness that results from melting.

In the asthenosphere heat conduction is, by hypothesis, generally less rapid than in deeper zones, in part because of lower densities. The transfer is locally checked and heat accumulation is promoted by relatively nonconducting layers above better conductors in the heterogeneous shell, that has resulted from repeated intrusions. Slight differences are regarded as adequate to produce marked effects, because they must be persistent during ages. We are considering processes in which a hundred thousand years is a fraction and a million years a unit of time. The effect of conduction would be gradual. More intense changes of temperature would result from the rise of magma, which must introduce large heated bodies into higher zones and there disturb the equilibrium of conditions. Thus the asthenosphere is regarded as a shell of potential disturbance at all times and of active disturbance from time to time.

The type of structure which may be taken as approaching that of the asthenosphere is that which is typical of the Archean. We are accustomed to assign to that structure a certain remote antiquity. From the point of view here taken, however, it may be considered as typical of conditions that determine the nature of intrusion and deformation in the "zone of flow." The results that we observe include horizontal sheeting and complex cross-cutting of igneous masses. Thus the structural units of the asthenosphere are taken to be sheets, flattened batholiths, and dikes, sometimes in large masses and again intimately interleaved, imbricated, and contorted. Metamorphism is thought to be general, except in bodies so recently solidified that they have not been subjected to the changes of temperature and the differential pressures that should result from intrusion and distortion.

5. The asthenosphere does not extend to the surface of the earth. Melting, its characteristic form of weakness, does not occur superficially except under isolated volcanic conditions that are of insignificant extent. The passage from the asthenosphere to the outer crust may be assumed to occur between 50 and 30 miles (80 and 50 kilometers) below the surface, and this outer crust represents the superficial skin in which

mountain-making deformation becomes evident in the features of the surface.

Asthenoliths

The term *asthenolith* has been proposed by the writer to designate a molten mass in the asthenosphere. The comparison with batholith is evident; but, since batholiths are relatively superficial and their history may be quite different from that of magmas developed at greater depths, it seems desirable to have a name that would distinguish such a deep-seated body of magma and would relate it to the zone of which it is a characteristic, dynamic incident.

The formation and history of the asthenolith has been presented in the paper, "Continental Genesis," already referred to. The concept is, however, basic for the ideas of metamorphic orogeny, and some repetition may for that reason be excused.

An asthenolith is by definition a molten mass intruded into or melted *in situ* in the asthenosphere. Where solidity is the rule, it is an exceptional condition, locally produced and further developed by a rise of temperature, which may be initiated by intrusion or by rise of temperature due to unequal conduction or to any other cause, and which is caused to spread to adjacent solid walls by continued inflow of heat.

An asthenolith is therefore a body which has a beginning, a prolonged history of development, a stage of decadence, and an end.

A local rise of temperature being postulated and its continuance assumed, so that the necessary energy may be available to supply the latent heat of fusion, melting may be regarded as a progressive process. The growth of the body of magma in any direction will proceed at a rate determined primarily by the relations of temperature and pressure and secondarily by local differences of composition of the wall rocks and the action of solvents. The former might be evaluated for a general case; the latter can not be; they may, however, afford explanations of exceptional phenomena and should not be overlooked.

Growth of the asthenolith may proceed by melting in either or all of three directions: upward, downward, and laterally. The dimensions of the molten body will be determined by the relations between the three rates of growth.

Open fractures in the walls are excluded by the excessive pressure due to the depth below the outer surface. Metamorphic structures are not excluded, however, and growth would undoubtedly be more rapid parallel to preexisting schistosity than across it. Metamorphism proceeding concurrently with melting should usually take place and would

result in schistosity parallel to the surface of the melt, according to observed facts and the laws deduced therefrom.

Pressures within the melt would be transmitted hydrostatically. They would therefore be uniform all over the surface and would everywhere balance the external pressures.

These things being postulated, we may consider the relative rates of growth upward, downward, and laterally.

Since the magma is heated at the bottom, the temperature at the upper surface is determined by convection currents promoted by the rise of gases. So long as melting is in progress in the magma itself, assuming the presence of refractory minerals, or on the lower surfaces, the temperature of the upper part can not exceed the melting temperature. Any excess of heat will be contained in the gases and they will constitute the active agents of solution. Their effect will be to produce contact minerals with the absorption of heat; and while to some extent corrosive, it will also be constructive. The rate of growth upward would depend largely on the gas content. Since it would penetrate into cooler layers, it would be checked by adverse temperature conditions and would probably be relatively slow.

On its under surface the magma receives heat by conduction from below, but carries it away by convection. The conditions of temperature and pressure are, by hypothesis, nicely balanced at the contact of magma and solid. Below that contact melting at the temperature of the magma is inhibited by greater pressure. It therefore seems probable that deepening of the magma by melting downward would be slight.

The chances of lateral growth seem more promising. Heat conducted to the lateral surfaces of the magma would cause convection currents to rise along them. The conditions of temperature and pressure, which, through their nicety of balance, first favored melting, would be found at the level of initial melting. Whatever solvent activity existed in the gases, whatever advantage of temperature over pressure might exist, would find their maximum opportunity at or near that level.

Lateral growth would therefore normally exceed vertical growth, and the usual form of an asthenolith would be that of a flat disk, of more or less rounded or oval form, provided the conditions of growth were equal in all directions.

The slow growth of an asthenolith being postulated on the grounds already discussed and its form being recognized as that of a flat bubble or blister, the question of size which may be attained is presented. To reach great size, long time is obviously requisite, but there does not seem to be any narrow limit set by the duration of geological conditions and

processes. A dynamic limitation appears more logically probable; that is to say, it seems likely that the molten disk might grow to such a diameter that the cover would rupture and the decadence of the asthenolith would begin with the escape of the magma. This leads to the consideration of the conditions affecting the stability of the cover.

Metamorphism of the Cover

Metamorphism of the wall rocks adjacent to igneous intrusions is a well-known phenomenon. In those cases which are exposed to view in Archean terranes the effects are often very pronounced and they extend to considerable masses. They are particularly intense in the covers of batholiths. Even so, they are the results of intrusion rather than of gestation or digestion. The process has continued for a short time only as compared with the period of growth of an asthenolith, and the depth of penetration into the wall rocks should be relatively small for the batholith, in contrast to much deeper penetration for the asthenolith.

The cover of an asthenolith, being subject to continued high temperature of the magma during a very prolonged period and constantly attacked by active vapors rising through the magma, could not escape intense metamorphism. If the conditions of temperature and gas supply be regarded as essentially stable, the metamorphism of the nearer layers would reach stability and the effects would gradually extend into more remote layers as the heat and gases rose into them. The transfer of heat will not be questioned, but there may be some doubt about the penetration of gases through schistose rock where all mechanical openings are closed. The phenomena of absorption of gases in solid rocks are, however, well established, and the capacity of the gas to penetrate molecular textures when aided by increasing agitation due to rising temperature seems to be a reasonable inference. A rise of temperature accompanied by an unbalanced stress would in any case be favorable to metamorphism.

It appears clear that the cover would undergo metamorphism, and it may be taken as probable that the process would penetrate to an indefinite distance above the body of magma during the millions of years of growth.

Schistosity requires for its development an unbalanced stress environment. In the presence of hydrostatic or balanced pressures, metamorphism would result in new minerals, but they would not assume the parallellism of axes that constitutes schistosity. It therefore becomes important to consider the conditions of stress in the cover, in order to ascertain whether it would develop a schistose structure or not.

That hydrostatic pressures exist in *solids* which are subjected to confining pressures beyond their crushing strength is a common, but erroneous

assumption. It disregards the difference between a solid which possesses a characteristic shearing strength and a liquid that is characteristically devoid of shearing strength. Resistance to shear is a definite characteristic of solids; force is required to overcome it. Parting on shearing planes which are definitely oriented is a mode of deformation characteristic of solids; it is due to definitely oriented stresses. These conditions are wanting in a liquid and their absence distinguishes that state from the solid.

This distinction between liquid and solid affects the nature of the stress distribution in the magma of an asthenolith as contrasted with that in the cover. In the liquid magma pressures are hydrostatic, even though the viscosity must be high. In the solid cover stresses are oriented, and equilibrium depends on internal shearing strength as well as on external pressures.

To make this important point clear, we may consider the conditions of equilibrium in a cube situated in the cover above the magma. The fact that it is in the cover implies that it is regarded as solid. It is subjected to a vertical load, P in figure 1, which is in excess of its shear-

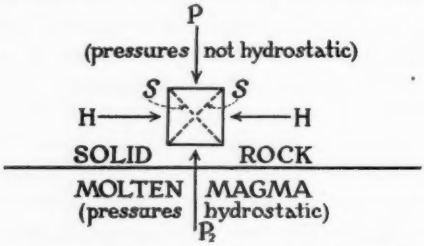

FIGURE 1.—*Conditions of Equilibrium in a Cube*
In case of stability, $P = S + H$ $\therefore H = P - S$, therefore H is always less than P if S has a finite value.

ing strength and would cause shearing if the cube were not laterally supported. Before shearing can occur, however, the resistance which the rock opposes to shear must be overcome, and that resistance is a finite quantity. The idea that excessive confining pressure reduces the strength of a rock still prevails in spite of Gilbert's clear-headed inference and F. D. Adams's demonstration that the reverse is true. Pressure increases the strength, presumably by promoting the cohesive bonds of the solid and augmenting friction. The actual resistance to shearing is therefore greater the greater the confining pressure. It is true that the increase of strength does not keep pace with the increase in load, and that the relative strength of the rock diminishes; but we are here concerned with the absolute finite value of the resistance to shear, and that is much greater than if the rock were not loaded.

Since the shearing strength of the rock has a notable finite value, it contributes to the stability of the stress system that is assumed to be in equilibrium. We may designate its value by S.

The remaining member of the stress system is the horizontal support, which is the lateral pressure that is developed between adjacent, hypothetical columns up to the point at which equilibrium is attained. Let us designate its value by H. Then, in case of equilibrium, H equals P minus S, for it is the residual stress required to produce the equation H plus S equals P, the equation of equilibrium. H can not exceed this value so long as the stress system consists simply of the vertical pressure, the resistance to shear, and the horizontal support.

Now, the requirement of hydrostatic pressure is that H equals P, a condition which can occur only if S equals zero. But if S equals zero, then the substance of the cube is a liquid and the condition of hydrostatic pressure should prevail. Or the assumption that hydrostatic pressure is induced by overloading is equivalent to assuming that the crystalline rock of the earth is fluid, which is not the fact.

From the fact that the cover of an asthenolith is solid follows the inevitable conclusion that it must oppose shearing strength to deformation by load. That strength is supplemented by a horizontal stress that develops up to the degree necessary for equilibrium under static conditions, and no more. Hence we must conclude that the horizontal stresses can never equal the load so long as the rock remains solid. Only when it is melted can hydrostatic pressures exist. Therein lies the distinction between the magma and the cover, considered as representing states of matter.

The stress environment being one in which vertical pressure exceeds horizontal pressures, the orientation of crystals will be governed thereby, as they develop in the process of metamorphism of the cover. Any individual molecule or microscopic crystal in moving from one position to another will be directed by the superior vertical pressure toward the inferior horizontal resistance. Its displacement will involve a small vertical component and a larger horizontal component. Its attachment in its new position will be determined by those molecular forces of attraction and repulsion which are superior to the cohesive forces, and it will exert a horizontal stress against the adjacent crystal. This stress is due to metamorphism, and to distinguish it we may call it the *metamorphic stress.*

The possibility of development of the metamorphic stress in a horizontal orientation is a fundamental concept of the theory of metamorphic orogeny and has therefore been critically considered with specialists in

physics, mechanics, and petrology. It appears to be sound and is accepted as a fact on which further deductions may be based.

Considering an asthenolith as growing, it is apparent that the metamorphism of the cover must be progressive from the initial area outward, and that the metamorphic stress in any direction must accumulate as crystal after crystal adopts the new orientation. We may suppose the resistance of the surrounding rock to be elastic in the early stages, but when the elastic limit is passed the rock must shear.

We may pause here to contrast the effects of metamorphic stress in the deep zone of "flow" with those that might develop in the zone of "fracture." The difference in the stress environment would produce quite unlike effects, other things being the same. In the zone of flow the superior vertical pressure would compel vertical thinning and horizontal extension. In the zone of fracture the superior strength of the surrounding rock would compel the metamorphic layer to shear inward, on itself, and to take up the effects of shearing by thickening vertically. The result would be uplift of the superincumbent mass. If the volume increased, the walls might remain stationary; but if the volume remained unchanged or diminished, the walls would move horizontally inward. The contrast of effects indicates that in the exceptional case of development of metamorphic stress in the zone of fracture vertical uplift will ensue, but in the case of action in the zone of flow horizontal displacement will result. The latter is the normal occurrence, since the growth of asthenoliths or other loci of high temperature is characteristic of the greater depths.

Rupture of an Asthenolith

An asthenolith is assumed to develop as a closed magma basin surrounded by crystalline rock which may or may not be of the same or similar composition. A difference of composition between the magma and the cover is not improbable, since the locus of melting is, by hypothesis, determined by difference of conductivity or by an obstructing layer in the path of ascent of a molten dike. In any case the basin is regarded as closed, and the conditions of rupture which may lead to outflow of the magma constitute a phase of the growing body.

It does not appear that any force competent to produce rupture of the walls can originate in the magma itself. It is undergoing a very slow process of digestion. The energy contributed to it is taken up in further melting. The processes of differentiation and gravitative separation inherent in the conditions do not develop excessive local stresses. The general pressures are hydrostatic and result in larger degree from the superincumbent weight than from internal expansion. We must therefore

seek conditions in the walls themselves to find the forces that may cause failure. The cumulative, metamorphic stress appears capable of attaining competency.

The molecular determination with which any single crystal may so transform itself as to elongate in the direction of least stress is very definite and powerful, but exceedingly minute in dimensional effect. It is only by the summation of such elongations that any mass effect can be produced. When, however, we consider that the diameters of an asthenolith may be measured in tens or hundreds of miles or kilometers, and that metamorphic elongation may be an indefinitely large percentage of the original dimensions of the cover, the possibilities become commensurate with the displacements of mountain ranges that we observe on the surface.

It is obvious that the growth of the metamorphic stress is related to the growth of the asthenolith in diameter. At an early stage, when the diameter is small, the total extension of the cover in any direction will be slight. The depth of metamorphism or the thickness of the metamorphosed layer of the cover will also be slight. As the asthenolith grows by continuous melting around the edges, the summation of crystalline elongations on any radius will become constantly larger. The compressive stress which it exerts in an outward direction must eventually attain a value equal to that of the shearing strength of the unaffected rock in front of it, and added increments of stress will cause shearing. This constitutes an initial rupture, but the process, like other phases of the life of an asthenolith, is ordinarily a prolonged one.

The effect of the shearing stress may be simple mechanical shear at 45 degrees, more or less, to the vertical, and of microscopic or macroscopic dimensions; or it may take the form of strain melting, the rock being very near the melting temperature.

A plane shear under intense compression would not offer any opportunity for intrusion of magma. A curved shear that resulted in displacement would be likely to do so, unless the curvature were spherical, which is improbable. A curved shear that resulted in displacement with a horizontal component would probably admit magma if initiated at the surface of the latter. It is not supposed that an open space could form in any case, but that the compressive stress might be lowered or even replaced by tension, so that a tongue magma would insinuate itself by virtue of the higher hydrostatic pressure exerted by it.

Any shearing plane, and especially any shearing plane that is lubricated by molten magma, whether the latter be intruded or autogenous, constitutes an inclined surface on which the metamorphic stress may and probably will be diverted upward. It is a surface of potential overthrusting.

The development of metamorphic stress, shearing, strain melting, and intrusion of magma are regarded as occurrences that lead to the ultimate rupture of the cover of an asthenolith and the escape of considerable amounts of the magma in the basin. We may look on this not as a sudden and individual event, but as an incident of the growth of the asthenolith, many times repeated and growing in effectiveness as the diameter of the cover and the intensity of the metamorphic stress increase.

Eventually the volume of magma escaping in consequence of shearing, strain melting, rotation of the cover, and overthrusting may be sufficient to remain molten until it approaches or reaches the surface and solidifies as a batholith, laccolith, or effusive flow of some sort. The initial stage of the life of the asthenolith may then be regarded as past and the structure may be considered to be passing into the longer stage of periodic activity.

Before passing to the consideration of the stage following the initial one, we may well consider the effect of repeated intrusions of magma into the cover in their bearing on the intensity of the metamorphic stress. It may reasonably be assumed that a holocrystalline rock may undergo greater change of form in consequence of metamorphic action through differential stress than would a schistose rock, already more or less metamorphosed. Whatever the original condition of the cover may have been in any given case, whether holocrystalline or schistose, it has become schistose by the time that the metamorphic stress is capable of producing shear, and it might be regarded as in a certain degree fatigued or not capable of as much elongation as originally, under the conditions of the case. Intrusive dikes constitute a source of renewed vigor. Solidifying from a molten condition under hydrostatic stress, they must crystallize with holocrystalline textures and should be capable of a maximum amount of change of form when metamorphosed. As long as dikes are small or few in number, their influence might not be significant, but as they increase in size and number their elongations may become an important, if not even a prime, factor in the extension of the cover. They may therefore contribute materially to repeated effects of deformation resulting from expansion of the cover. The very general metamorphism of igneous rocks in the Archean suggests the nature and persistence of the process.

Mature Activity of an Asthenolith

The initial stage of an asthenolith has been described as that during which the magma increases in volume to the degree that rupture of the cover occurs and outflow of magma begins. The conditions which cause

the increase in volume are deep-seated and not directly related to those that cause outflow. They are independent, original causes and may be assumed to continue without disturbance by the outflow. The volume of magma at any subsequent episode will be the difference between that which is produced or and intruded and that which is extruded. This statement assumes that new magma may be produced around the margins or from the upper and lower walls of the asthenolith and also that the body may be fed by dikes rising from deeper sources.

The period of activity thus characterized may be compared with that of maturity in the life of a man, the relatively long period during which he is most vigorous, and which is known as maturity. Following the initial stage in the life of an asthenolith comes the very long phase during which the forces of the magma basin do the most effective work, and which we may designate the *mature phase* of development.

Emphasis is here laid upon the great duration of the mature phase partly because that interpretation is consistent with the facts of geology and also because in a related branch of orogeny, physiography, the use of the term has been limited by Davis to a definite episode of the topographic cycle of erosion. The concept of prolonged maturity appears to be more in accord with the ordinary English use of the word.

During the period of maturity accessions of heat are supposed to continue. They will come by conduction with essential regularity. They may also come by intrusion from below, and thus occur pulsatingly, periodically, or paroxysmally. The former would produce steady growth, other things being equal. The latter would result in episodes of marked activity, which might be expressed in specially vigorous increments of metamorphic stress, or in powerful eruptions, or in both.

We have hitherto discussed an asthenolith as an individual magma basin growing independently of others, but when we contemplate it as one of an ascending series the possibilities of growth and activity are materially enhanced. The series may be regarded as originating in an autogenous dike in the stereosphere and as comprising not merely one but several asthenoliths situated at different depths, one above another in the asthenosphere. Since, as has been pointed out, eruptions of magma probably rarely follow a vertical, radial course, but are more likely to take diagonal paths in adjustment to shearing planes, it would follow that the members of such a series of magma basins would usually rise by offsets, in a stairway as it were.

In case an asthenolith receives a notable influx of magma from below, the temperature and pressure of the intruding mass will be higher than those of the superior basin and the dynamic activity of the latter will be stimulated. The cover will probably be domed up and notable

lateral growth of the magma basin might ensue. The metamorphic stress would be stimulated and powerful; lateral thrusts might occur.

In case an asthenolith erupts without influx from below, the volume of magma in the basin must be diminished. According to the analysis already presented, the eruptions would assume diagonal paths outward from the margin. The erupted masses would therefore come to rest outside of the circumference of the asthenolith and at a distance from it which would bear some relation to the height they had attained above it. If they failed to reach the surface of the earth, they would form a more or less discontinuous ring of swellings. If they penetrated to the surface, they would constitute a volcanic range, in which, however, volcanos would be individual peaks associated with folded and overthrust masses, displaced by the lateral pressure of the metamorphic stress. The latter may be regarded as acting against temporarily diminished friction because of the lubricating effect of the intruding magmas.

The outflow of magma from an asthenolith will affect the cover by depriving it of support. The only support the cover has from the beginning of melting on through the life of the structure is the confined magma. When the latter escapes the cover must sink in to occupy the volume that would otherwise be void. When thus deprived of support, the cover may be regarded as a slab resting on its edges and it will sink accordingly. Any previous doming effect will be lost, and it may become so far depressed below the normal curvature of the globe as to constitute a concavity or basin.

This analysis indicates that the changes which occur during the maturity of an asthenolith are such as to produce a ridge or mountain range around it, comprising folded and thrust masses and volcanos, while over the position of the magma basin there develops a depression in the surface. These are the characteristic features of the individual deeps that are included in the greater ocean basins and constitute their accents.

Among the effects of subsidence of the cover and the formation of a concavity on its upper surface will be the convexity of the under surface and a tendency toward tension in layers near the magma. Intrusion of the latter in the form of dikes would logically follow. The dikes would assume vertical attitudes. If they congealed before reaching the surface, they would furnish holocrystalline rock capable of metamorphism in high degree and of adding to the metamorphic stress. If they extended to the surface, they would flow out on the bottom of the basin and exchange levels with the upper part of the cover. They might result in extensive flows or in volcanos, according to the nature of the lava and the conditions of eruption. The points of outflow would

probably in the majority of cases be determined by fractures and would assume a linear character. These also are features of ocean beds.

Active Asthenoliths

Any discussion of the dynamics of the interior of the earth must necessarily be speculative, since the actualities are beyond the reach of observation. The best we can hope to do in the way of demonstration is to deduce processes that are in accord with the laws of mechanics and physics and that produce results such as we can observe in superficial features of the globe. We have examined the deeper dynamic zones and have endeavored to analyze the conditions of activity. We have traced the latter to a hypothetical expression at the surface. It now remains to test the deductions by comparison with the facts that we can observe.

It is appropriate to state that the process of development of the theory of metamorphic orogeny here presented has been just the reverse. The concepts that I now entertain as a working hypothesis have developed during the past forty-four years, as the result of observations in various parts of the world. In 1885 G. K. Gilbert set me the problem of the mechanics of Appalachian structure and his kindly wisdom guided the initial studies. They resulted in the conviction that horizontal compressive stresses had accomplished greater effects in folding and overthrusting mountain ranges than could be accounted for by gravitational contraction or settling, and that another and greater force than gravity had been and is at work. It appeared, furthermore, that the horizontal displacements are of such magnitude and are so localized that they could not extend to a sector of the globe having its apex at the center, but must be relatively superficial overthrusts of a comparatively thin sheet or scale, possibly 100 miles (150 kilometers) thick. Early views to the effect that the active source of pressure that caused the Appalachian folding had been continental gave way to the accumulating evidence that the sources of pressure are suboceanic. The mountain ranges around each ocean basin, even around the vast Pacific, have had approximately contemporaneous developments, whereas the orogenies of opposite sides of each continent have differed markedly in their histories. The ocean basin is therefore the dynamic source of pressure. The idea that suboceanic masses exert the pressure in consequence of expansion in a horizontal direction was a logical sequel.

Barrell and I independently postulated the forces of recrystallization as the probable form of energy. He unfortunately did not live to work out a complete theory of the mechanism by which the forces might operate, nor did I for twenty-five years discover any suggestion of the

conditions that would result in the appropriate orientation of the stresses.

Heat seemed to offer the most promising form of dynamic stimulant to bring about an orogenic revolution, but it was subject apparently to severe limitations. The geologic evidence of prolonged stability of very large areas of the earth's surface seemed to forbid assumptions involving the existence of large, extensive bodies of magma beneath the surface, since it was thought that tidal effects would cause obvious disturbances in the superficial crust, and that eruptions would demonstrate the presence of the magma. There being no trace of such tidal effects in many cases where they were to be expected, the postulate of molten foundations seemed ruled out. Heating without melting was thought to occur, but the effects attributable to it did not seem to correspond in degree or kind with the requirements of orogeny and vulcanism.

In 1926, while considering the related problem of the batholiths, I became convinced, in discussion with N. L. Bowen, that the requirements of petrology made it necessary to postulate much larger volumes of molten magma than I had been willing to admit could occur in the earth's outer shells. Doubts being raised as to the validity of the argument concerning stability and tidal disturbance, they were confirmed by an investigation of marine tides. The Mediterranean, for instance, exhibits but a very slight tide in its main body. If a free water surface of those dimensions did not respond more evidently to the attraction of the moon, what should we expect of a body of viscous magma buried many miles below the surface of the earth? Obviously nothing that could be detected by geological criteria. Conferences with professors Michelson and Moulton, the tidal experts, definitely settled the point. The differential rise and fall due to such a mass of magma might roughly amount to a small fraction of an inch. The disturbing effects could not affect the eruptivity of the mass. We are therefore free to consider what, if any, features of the actual ocean basins and continents might correspond to especially dynamic regions in which heat is the dominant form of stimulative energy.

Such regions are not difficult to find. They are characterized by volcanic and seismic activity. The differences of relief within them comprise the greatest elevations and the deepest depressions; from sea bottom to mountain top is often as much as 30,000 feet (10,000 meters). There is abundant evidence that the great cordilleras, although now in a youthful stage of the topographic cycle, have had a long orogenic history. Their beginnings date back to the late Paleozoic or Mesozoic. They have grown vigorously during the Tertiary and have been rejuvenated during the Pleistocene. There is every reason to infer that

the adjacent oceanic deeps have experienced contemporaneous and related changes. The deep and the cordillera are members of a common structure in which heat has throughout its history been an active force, as is indicated by periodic vulcanism.

The Atacama Deep, that stretches along the western margin of South America past Peru and Chile, is a typical example of the structures that appear to conform to the preceding description and to be long-lived but still active asthenoliths. The very deep itself conceals the facts of its structure and history, except that the few soundings show it to be a great deep. Approximately 500 miles (800 to 1,000 kilometers) off the continental coast, there is a ridge on which the depth of water is still 16,000 to 18,000 feet (5,000 to 6,000 meters) and from which rise the volcanic islands of the Juan Fernandez group and the islets San Felix and San Ambrosio. They are the summits of large volcanos and indicate that the entire ridge is a volcanic pile. It is possible, however, that it is in part a pressure ridge similar to other mountain ranges.

Some distance to the east of the deep, it may be 50 or 100 miles (80 or 160 kilometers), the margins being ill-defined, the depression is paralleled by the coast range of Chile, beyond which rises the great Cordillera of the Andes. My personal observations of this coast comprise the stretch from latitude 18° south (Arica) to 43° south (Colonia de Diez-i-Seis-de-Octubre). Portions of it have been described by Quensel, Schiller, Stappenbeck, and others, including Steinmann and Walter Penck. It being impossible at the present writing to refer to the literature more specifically, I shall confine myself to a brief statement of the dynamic history of Atacama.

The Province of Atacama, in northern central Chile, lies east of the central section of the Atacama Deep and may be taken as presenting in a general way the characteristics of the Cordillera to which the deep is, by hypothesis, causally related. Dynamic activity of the Andean orogenic period began in Atacama, in late Paleozoic or early Mesozoic time, with the intrusion of granite into the zone of the modern coast range. Fine sediments such as are characteristic of epicontinental seas had previously accumulated on a subsiding sea bottom and indicate a gradual epeirogenic movement that must also have included uplift of an adjacent land. The intrusion of the granite was the first evidence, so far as we can determine, of any disturbance of the quiet conditions that had prevailed.

There are two possible interpretations of the disturbing conditions: The one is that the quiet period was evidence of the solidity of the earth to a distance from this region and to a depth such that the existence of a magma basin could not modify the state of stability that reigned.

This implies that the granite either came from very great depths or had been solid and was remelted shortly before the intrusion occurred. The latter is the view which I have set forth in the report on earthquake conditions in Chile. In opposition to that position it is argued by petrologists that granite, if melted and resolidified, does not yield granite. That fact appears to be demonstrated to the satisfaction of the petrologists of the Geophysical Laboratory at Washington by their experimental results. If open to question at all, it is so merely because the conditions of resolidification within the globe transcend any possible laboratory conditions and may accomplish results that we can not imitate. In consideration, however, of the experimental evidence against remelting of the granite, it seemed wise to seek an alternative explanation, and that search led to the evolution of the idea of asthenoliths.

According to the latter the alternative state that existed during the period of quiet was that of the growing asthenolith before it was ruptured. The existence of the magma basin is not regarded as opposed to the stability of geologic processes. The slow growth of the asthenolith in diameter and the gradual development of the metamorphic stress are assumed to have been the causes of pressure that produced uplift and subsidence of the geanticlinal and geosynclinal type. The differentiation of the granite from the more basic magma went on in the magma basin concurrently with the growth, and the eruption of the granite followed as the first sign of the activity for which the forces had been gathering during a very long period. This latter explanation is more consistent with the facts and with the nature of terrestrial processes than the former and is therefore here preferred.

Eruptions from the magma basin have continued from time to time during the Mesozoic, Tertiary, Pleistocene, and Present. A great variety of magmas has been forced to the surface. The granite was shortly followed by diabase and melaphyre. During the Jurassic very large volumes of labradorite were poured out. In Tertiary time the lavas ranged from andesite to basalt, and similar types have recently been and are being erupted. Neither the sequence nor the dates of eruption are necessarily similar throughout the length of the great zone of the Cordillera. Thus the granite, which in Atacama is certainly early Mesozoic and possibly Paleozoic in age, appears not to be represented several hundred miles farther north, near Chuquicamata, where there is, however, a similar granite that was erupted during the Cretaceous, as described by Whitehouse and Lindgren. There is a most promising field for petrologic and structural study awaiting investigation in central and northern Chile, and its results will bear very directly on the unity or diversity of the magma basins or asthenoliths from which the various products have come.

The granite of Atacama was intruded into the zone which now constitutes the coast range. Small outcrops of it are known farther east, but the volume they represent is indeterminable because of the large outflows of later lavas that obscure the basement rocks. The meager evidence suggests that the granite is not a conspicuous member of the igneous series in the Andes of Atacama. However that may be, the Mesozoic eruptions occurred in a zone east of the coast range, where they constitute the dominant rocks of the western slope of the Cordillera and extend in volume to the high plateau. Intruded through the eastern part of the Mesozoic zone and forming the mass of the great heights are the Tertiary and later volcanics. Thus there is from west to east a progressive sequence comprising earlier eruptions in the west and the latest in the east.

The Atacama section of the coast range and Cordillera is characterized structurally by a large number of thrust-faults which extend parallel with one another, trending a little east of north. They divide the igneous and sedimentary terranes into strips from 2 to 5 miles (3 to 8 kilometers) wide and they dip rather steeply west. The great earthquake of November, 1922, and other strong shocks, which have been adequately described by Montessus de Ballore, indicate by their manner of occurrence that these numerous thrusts extend down to a major thrust-plane, or sole, and thus form part of an active structure of the Scottish Highland type.

The evolution of this structure is of notable interest. In the west, in the coast range, and the western slope of the Andes below the greater heights, the thrust-faults no longer affect the topography in a conspicuous way. They are relatively old, early to late Pliocene probably, and the scarps have been so modified by erosion that their tectonic character is no longer recognizable. Moreover, they do not break the continuity of the gravel terraces that resulted from the Pleistocene valley filling and the subsequent changes of grade. Farther east, in the higher Andes, about the head of the Rio Elqui, for instance, fault-scarps of recent origin are conspicuously developed. They are distinctly younger than anything farther west. The eastern slope of the Cordillera is said by Keidel, Felsch, Schiller, and others to be marked by active thrusts that transect the recent alluvial cones. These are even younger. Thus the development of the thrust structure appears clearly to have begun in the west and to have progressed eastward. In this progression the structure and the volcanism have kept step with one another.

From the point of view of the hypothesis here put forward, the dynamic history of Atacama is the surface expression of the growth of one or more asthenoliths situated beneath the Atacama deep. If one only, it is a very large body of magma, possibly between 50 and 100

miles (80 and 160 kilometers) below the surface. If, as is, perhaps, more probable, there are several bodies, they may be independent of one another or related in a stepped sequence with dikelike connections. The asthenolithic growth would have begun during the Paleozoic, long prior to the eruption of the granite, and the initial period of growth and gestation would have come to an end with that eruption. The subsequent period of maturity has then covered all the following geologic ages. There were, no doubt, early effects of the metamorphic thrust. If exerted at great depth, they may have taken the form of compression of the foundations of the coast range and Cordillera, thus causing at the surface only vertical elevation; but the later effects are distinctly recognizable in the great progressive overthrust structure of the Andes of Atacama.

We turn next to California. An orogenic period which may be regarded as continuing down to the present day began with the intrusion of batholiths of granodiorite, of which two at least are easily recognizable—the batholith of Lower California and that of the Sierra Nevada. The former extends from the southern end of the peninsula of Lower California throughout its entire length and may probably be represented by the occurrences of granodiorite in the Coast Range of California proper as far north as the Bay of Monterey. The Sierra Nevada batholith is coextensive with the area of that well-defined mountain range. It has been described as curving around the southern end of the Great Valley of California and connecting with the occurrences in the Coast Range, which are here linked with the Lower California mass. The reason for taking the latter position is that the great San Andreas fault, which extends for 600 miles (900 kilometers) lengthwise of California and lies for a part of its course between the two batholiths, appears to separate them and to be itself best explained as the effect of the overthrust of the Lower California batholith upon the Sierra Nevada mass.

The date of intrusion of the Sierra Nevada batholith was not earlier than Upper Jurassic, as determined by fossils. The intrusion of the Lower California batholith is not so well dated, so far as I know. The northern occurrences that are here correlated with it penetrate limestones that are tentatively regarded as Paleozoic, and it is possible that they were placed before the Sierra Nevada granodiorite rose toward the surface. In that case the relative ages of the two great intrusions would approximately parallel the appearances of the granite of Atacama and that of northern Chile, as already described; but no weight can be attached to this possible coincidence.

The eruptivity of California was continued by the vulcanism of the Franciscan period. The rocks are prevailingly very basic. Their

volume is large, but they are confined to the Coast Range. The date commonly assigned the activity is late Jurassic or possibly early Cretaceous. The basic rocks are certainly later than the granodiorites of the Coast Range, which they cut.

The upper Cretaceous was marked by a cessation of volcanic activity—a pause that finds its analogue in the Chilian history. Then in Tertiary times vulcanism was renewed on a large scale, not in the Coast Range, but in the Sierra Nevada, much farther east. It continued during the late Tertiary and in minor degree into the Pleistocene. There is still some slight activity.

The structure of the Coast Range of California resembles a joint system in granite on a very large scale. The master joints are faults of very great displacement. Their length often exceeds a hundred miles and may attain two or three hundred. This statement is exclusive of the San Andreas rift, which is 600 miles long and may be an exceptional major structure, as already explained. The trends of the faults are from southeast toward northwest, in a general way, but they assume more or less pronounced crescentlike forms, and each crescent is seismically the locus of earthquake shocks in some degree independent of adjacent crescents. This appears to indicate that they are dynamic units. The master faults branch at acute angles and the strips between them are traversed by very many cross-faults. Within the blocks thus cut out there is local, but strongly developed, folding of the sedimentary rocks of Cretaceous and Tertiary ages. The entire structure is the product of compression. Its type is determined by the prevalence of massive rocks in the foundations of the ranges and is therefore characteristically marked by shearing in lieu of folding. The effects are most intense in the strip between the San Andreas fault and the coast, and the deformation of the Coast Range as a whole is more intense than that of the Sierra Nevada and other ranges farther east. The active pressure, therefore, came from the oceanic side. The passive resistance was continental.

A very marked bend from the southeastward trend of the Coast Range to a nearly eastward trend occurs on the coast of California and is shared by the ranges and the San Andreas rift. If the latter marks the shear zone between the two great batholiths, this turn may correspond with the northern end of the batholith of Lower California, except in so far as the intrusion may be represented farther north by a less massive tongue or by discontinuous masses.

The eastward turn in the ranges encircles the southwestern side of the Central Valley of California and is a locus of extreme faulting and folding. The Coast Ranges are forced against the rigid mass of the batholith of the Sierra Nevada at its southern end. The Valley is a depressed block, deeply buried beneath Tertiary and Pleistocene sedi-

ments. Beyond it lies the even larger block of the Sierra Nevada, which has been described as simply tilted but is now known to be tilted and uparched, the arching being accompanied by upthrust faulting.[5]

On the oceanic side the continental plateau of which California is the western strip descends rather abruptly into a deep that is one of the marked concavities of the Pacific Ocean bed. It is coextensive along the coast with the characteristic structural types which have been described, reaching from the southern point of Lower California to the latitude of the northern end of the Sierra Nevada. At the northern end, where the deep shallows to the general level of the ocean bed, an older mountain group, that of the Siskyous, forms an island of Paleozoic and more ancient metamorphics surrounded by Cretaceous strata. The relation of position between the deep and the mountain ranges of California suggests a relation of genesis. Interpreting the deep as the basin over the collapsed cover of an asthenolith, we would regard the two batholiths as eruptions of the more acid differentiates of a magma basin that had attained maturity. The basic volcanics formed the later extrusions. Since there are two batholiths and their relative ages are indeterminate, there is room for several postulates as to the sequence of eruptions. It is also possible that two or more asthenoliths, either independent or connected, may have taken part in the activity.

The development of the major faults, which are of pre-Tertiary and probably in some cases of pre-Cretaceous age, indicates the early action of the compressive stress from the oceanic side and can be interpreted consistently with the theory of metamorphic orogeny as the effect of the metamorphic stress. The orogenic period which was thus initiated has continued with pauses down to the present. The earthquake activity is a nearly continuous manifestation of the pressure, and its localization in minor crescents suggests that the still expanding cover has a crenulated margin. We would naturally expect that some radii would have grown more than others, and that pressures would be localized and intensified on certain sectors.

In the earthquake in northern California in 1906 there was a very decided horizontal displacement of one large block past another. The dividing plane between the two was the San Andreas rift, which is vertical at least in its upper part. The block of the continental margin lying southwest of the rift was moved on an average 8 or more feet toward the northwest, past the continental block northeast of the rift. The movement occurred in a few seconds and was observed along the rift for 180 miles (288 kilometers). As the focal depth of the earthquake was about 25 miles (40 kilometers), this means a displacement

[5] Bailey Willis and Robbin Willis: Geologic structures, 2d ed., 1929.

on a vertical plane having a superficies of 180 by 25 miles or on the margin of a large disk. As the displacement extended at its northern end beyond the possibility of observation under the Pacific, it involved a larger mass than has been stated. The most reasonable interpretation of this movement appears to be to regard it as a rotation of the disk thus partly outlined by the San Andreas fault. If that interpretation be in turn explained by the hypothesis of an asthenolith, we recognize the rotation as an effect of the internal expansion of the cover and of unequal pressures against the surrounding rim.

The examples described from Atacama and California have many similarities, but they also present an instructive difference in structure. In Atacama the faults are low-angle overthrusts; in California they are high-angle upthrusts, with a pronounced horizontal component in some cases at least. In Atacama the displaced blocks are very long and narrow strips; in California they are blockier, though of somewhat elongate form. In Atacama the general effect of displacement has been to crowd the edge of the continent eastward; in California there has been something of the same eastward movement, but the individual blocks have been more strikingly raised or depressed or squeezed out of place longitudinally, according to the form of their under surfaces. Being bounded by shearing planes, they have moved as a wedge moves when pressure is exerted against its sides, in the direction away from the thin edge, upward or downward or upward and longitudinally. These differences in structure between Atacama and California are presumably due to the differences in massiveness of the batholithic intrusions, which are relatively small and scattered or dikelike in the Chilean region and of exceedingly large volume and massive structure in the Californian cordilleras.

Japan, the Philippines, and New Zealand appear to present examples of asthenolithic development not unlike those described, but with pronounced variations of igneous history and structural development. While my observations in those countries suffice to lead me to that inference, they do not yet justify a more detailed analysis and comparison. Alaska also and the Aleutian Island chain invite study from this point of view.

Active asthenoliths, dating from late Paleozoic or early Mesozoic time, appear to be characteristic features of the Pacific basin—that is, of one hemisphere of our globe. They seem competent to furnish the forces and the mechanism of the orogenic processes that have developed in the adjacent continental borders during their existence.

Extinct Asthenoliths

The Atlantic basin presents a history different from that of the Pacific. Since the early Mesozoic, inactivity has been characteristic of all its deeps, both north and south, except that since the middle Tertiary the adjoining lands have been gently warped and volcanic ridges have been erupted along a few arcs. There is nothing to compare with the contemporaneous volcanic, seismic, and orogenic activity of the Pacific deeps. Yet the Atlantic basin also had its active period.

The latest orogenic period or orogeny of the North Atlantic was that to which Dana gave the name of the Appalachian revolution. He confined the application of that name to the episode of folding and overthrusting with which the great movement closed, and it is well to use the term "revolution" in that sense. But revolutions are always preceded by a period of gestation and the dynamic entity should include both. The *orogenic period* should therefore cover the interval preceding the revolution, during which there occurred the deepening of the geosyncline, the uplift of an adjacent land, and the preparation for the final efforts. If thus applied, the Appalachian orogenic period covered Carboniferous time and extended into the Triassic. The earlier orogenies of the Devonian and Silurian might be included in one very prolonged development, but modern geologic thought has not yet taken so comprehensive a view. The earlier orogenies did, however, develop in the same basin and from similar, if not the same, deeps.

Taking the Appalachian revolution as an example of Atlantic orogenies and including the period of gestation, we recognize the well-established facts of quiescence during the Mississippian period, renewed activity of uplift, erosion, and sedimentation during the Pennsylvanian, and ultimately the folding and overthrusting. There is nothing in these movements themselves to indicate a relation to a body of magma and the metamorphic stress we have postulated. The "revolution" was, however, marked by the intrusion of granite into the eastern portion of the Appalachian zone throughout its entire length. The intrusions are so generally present and are of such volume that two careful observers, Shaler and Keith, have ascribed the compression to the intrusion. The granite undoubtedly intruded forcibly and displaced the masses beside it, but it did not itself possess the force to do the work. It must have been subjected to pressure that not only raised it from deeper levels, but also sufficed to force it into the country rock. That pressure was the real cause of folding and

faulting, and the source of that pressure, as also of the granitic magma, was beneath the adjacent Atlantic deep.

On this basis of facts and by analogy with the more complete examples of later Pacific history, we may infer that an asthenolith (or several) developed under the Atlantic east of the land called Appalachia at least during the Mississippian period; that a metamorphic stress grew in the cover and in Pennsylvanian time pressed the land upward. Deepening of a geosyncline somewhat to the west of the older trough went on simultaneously and sedimentation followed *pari passu* with the deepening. The stress sheared the cover of the asthenolith and afforded opportunity for the escape of the granitic magma, which had become differentiated during the period of gestation. The magma rose not merely by virtue of hydrostatic pressure, but also because the metamorphic stress was exerted on the rocks into which it intruded, and it was thus forcibly squeezed upward in the direction of least resistance. That under these circumstances it exerted a compressive stress against the rocks in front of it, there can be no doubt. The effect would, however, be of a local nature and not sufficiently uniform in distribution and application to develop the remarkably parallel structure of the Appalachians. That folding and overthrusting requires a more uniformly distributed pressure, such as would be produced by metamorphism of the cover of an extensive asthenolith.

The Appalachian structure, which is universally recognized as characteristic of the region, is that of the folded and overthrust Paleozoic sediments. It was fully described, in a manner that has not been bettered in fourscore years, by the Rogers brothers, and is the typical example of folded structure. In 1889, when Gilbert was discussing the experimental results obtained by me under his direction and published in the "Mechanics of Appalachian Structure," he remarked that folds of that character could not extend to any great depth. It was his opinion that a relatively thin wedge had been sheared off and folded up in being pushed over the basement rocks. Rollin Chamberlin subsequently, by original and independent investigations, proved Gilbert's idea to be correct; that is to say, the folding is shallow and it and the thrust-faults go down to a shearing plane, or sole, that underlies the whole structure. Were the compressed mass cut through to the basement rocks beneath the sole, we would presumably see a complete structure of the type that is exposed in the Scottish Highlands and that is regarded as the structure of Atacama, already described.

The thicker end of the displaced wedge lies toward the east. From under the folded zone the sole, or great major thrust, extends eastward under the mountains of pre-Cambrian rocks, known as the Smoky Mountains of North Carolina and the Blue Ridge of Virginia. Keith

has described the complexities of the great thrusts in the Roan Mountain region. They represent deep-seated displacements, plicated and thrust again in the continued westward advance of the wedge. The habitat of the granitic intrusions is in the thicker end of the wedge. They were forced into it and accompanied it in its advance. These facts all point to the conclusion that the wedge was sheared off of the margin of the continental plateau by pressure exerted from beneath the oceanic deep. According to the view here entertained, that pressure originated in the metamorphic stress developed in the cover of an asthenolith, and the granite was part of the magma erupted from that body.

The preceding statement of facts and inferences is most nearly correct for that portion of the Appalachian zone that extends from Pennsylvania southward to Georgia. In that stretch there is a complete absence of igneous rocks in the typical western folded belt and relatively little, where there is any, representation of basic igneous rocks with the granite in the eastern metamorphosed belt. The northeastern New England section of the Appalachians had a more complex history and comprises a greater variety of igneous rocks. Silurian, Devonian, and late Paleozoic orogenic movements have been recognized between Pennsylvania and the Saint Lawrence River. The general facts of intrusion and horizontal compression are consistent with the view that they proceeded from one or more asthenoliths and the metamorphic stresses thereof.

The parallelism of orogenic episodes and revolutions that was first worked out by Murchison and Sedgwick and by their American colleagues, Hall, Dana, and others, for the British Isles with America, is a provincial fact of the North Atlantic basin. It has given us a geologic chronology which, though local, has become standard for the whole world. It serves a useful purpose as a standard, but we shall make progress when we recognize that periodicities are provincial, are most closely to be correlated within individual ocean basins, and do not synchronize across continents.

According to the hypothesis of metamorphic orogeny, the parallelism between the geologic histories of the British Isles and northeastern North America is to be explained on the postulate that the orogenic activities around the North Atlantic originated in one or more asthenoliths which, if several, were closely related. It is a remarkable parallelism. It dates at least from late pre-Cambrian time, was recorded during the Paleozoic, Mesozoic, and Cenozoic eras, and is still evident in the close likeness of seismic activities in Great Britain and New England. The land connection that existed during Coal Measure time around the North Atlantic may be regarded as an Isthmus of

Iceland in the sense that we speak of the Isthmus of Panama and, like the latter, may well have been the raised rim between two deeps: the North Atlantic and Arctic deeps in the one case and the Caribbean and Eastern Pacific deeps in the other. In both instances the dynamic evidences are similar and are those we attribute to the activity of asthenoliths. The rupture of the Isthmus of Iceland would seem to have occurred when the final revolution emptied the asthenolith and caused the rim to subside from the elevated position to which it had been thrust by the metamorphic stress. The suggestion is one which finds application in many instances where previous land connections are demonstrable and submerged ridges can now be traced between the continents. As an alternative to the bald assumption that whole continents have disappeared, it has the advantage of moderation and consistency with known phenomena.

Extinct asthenoliths older than the Paleozoic are necessarily pre-Cambrian in age, and their occurrence within areas where observation is possible is confined to the continental shields and other positive elements. This subject has been treated in my paper, "Continental Genesis," printed in Part I of this volume. The thought carries back into still earlier times without finding any reason to set a limit to the possibilities of development of the type of magmatic reservoirs here postulated. If the argument for their actual existence be sound, there is no epoch of the past to which it would not apply since the earth grew large enough to have a heated core and an asthenosphere. From this point of view the outer crust, the asthenosphere, and possibly part of the stereosphere, passed through stages of eruptive activity that involved all the processes incidental to the lives of successive asthenoliths.

Collateral Tests

The ultimate test of a theory of orogeny is the satisfactory demonstration of its ability to explain a number of instances of mountain growth in a manner consistent with the laws governing the inferred processes and with the development of those processes. From that point of view there are many cases by which the theory of metamorphic orogeny may be tested. Among them are further studies of the great cordilleras that characterize the American borders of the Pacific from Cape Horn to the Aleutians, and their related branch in the Antilles; the Asiatic and East Indian arcs; the Himalaya range; the surroundings of the Mediterranean and the diminutive but intricate mosaic of European ranges, including the Alps. The subject is too vast for treatment in such an article as this and demands resources beyond those of an individual. We leave the special cases for the future and

turn to consider some general tests of consistency of the theory with facts of orogeny.

The prolonged existence of large bodies of magma in the earth appears to be required by the evidence of intrusions into the outer crust at all times from pre-Cambrian to mid-Tertiary and by the results of petrologic research. The bar to acceptance of this conclusion has been removed by the results of tidal investigations, which show that the existence of such magma basins is not inconsistent with that stability of the surface of which there is independent evidence. Postulates regarding the origin of such bodies may vary without affecting the fact of their existence. Batholithic instrusions younger than mid-Tertiary are not uncovered, but the volume of younger effusives is large and there is no reason to suppose that the eruptive activity has diminished since that recent period. The actual existence of asthenoliths at the appropriate depths and in the appropriate relations of position with reference to surface features is an assumption that is most consistent with all the evidence we can gather from the past and present.

Metamorphism and the development of a metamorphic stress in appropriate orientation are logical conclusions from the manner and conditions of the growth of the magma body. The outward pressure exerted by the metamorphic stress is found to be properly directed to produce the phenomena of compression in which the problem of orogeny originates. There are, however, in this regard certain residual questions that spring from a difference between fact and theory.

Theoretically, an asthenolith should grow into a disc-like body with a rounded outline. There are oceanic deeps which approach that form. They occur significantly far from continental margins, the ridges that surround them are submerged, except perhaps for volcanic islands, and too often the outlines are not yet sufficiently known to be accepted with confidence. Against this somewhat uncertain evidence of rounded asthenoliths we must place the fact that those which border the continents and appear to be related to cordilleras are decidedly elongate in form and unsymmetrical in cross-section. The map of the concavities of the earth's surface prepared by Emmons for the "Manual of Geology," by Chamberlin and Salisbury, shows this to be the fact for all modern deeps that are here regarded as active asthenoliths. They parallel the continental outlines. In this fact lies, presumably, the cause of their departure from the ideal form. The asthenoliths are deep-rooted. Their roots are in the original zones of stress and eruption that located the continents, and the modern lineaments reflect the geographic features of a remote antiquity, during which the major basins and the continental plateaus were laid out. Any

asthenolith developing adjacent to an older one is liable to resemble the latter in form because of persistence of the deep-seated stresses that gave rise to it. If the older was so constituted that differentiation of the magma resulted in segregation of granite and eruption of batholiths which contributed to a continental mass, the younger is likely to continue the process of continental growth. The Pacific coasts of the two Americas give evidence of this process.

Asthenoliths appear normally to erupt different magmas from opposite sides, at some period of their activity at least. Thus the earlier eruptions from the examples that have been described were in each case of granite or granodiorite. No similar eruption appears to have occurred on the oceanic side. Either there was none or it was more basic. The persistence of this unilateral intrusion of granite points to the existence of a related source of acid magma or of magma capable of that phase of differentiation on one side and to sources of distinct magmas for other parts of the basin. The singularity of granitic eruptions, which are not repeated at short intervals as the more basic are, also points to special conditions of gestation and differentiation peculiar to a certain stage of development of the magma body. Granite seems to be a product of the long period of preparation that precedes the earlier eruptions and to be exhausted during them.

The dissymmetry of asthenoliths when they border continental masses extends also to the action of the pressures. The Andes have no counterpart on the other side of the Atacama Deep. Parallel mountain chains do not occur in twin arrangements. An analysis of the variables to which we may attribute the dissymmetry shows that they are numerous and can not well be evaluated with our present knowledge. They comprise at least (*a*) conditions affecting the growth of the metamorphic stress, such as greater sensitiveness to metamorphism or greater capacity to extend forcibly, provided the constitution of the cover were not the same on two sides of an axial line; or (*b*) conditions affecting the resistance of the margin to displacement, such as the relative strength opposed to shearing, the rigidity or capacity to transmit stress to an appreciable distance, and the friction developed on planes of thrusting; or (*c*) the relative weights of masses to be moved; or (*d*) the influence of a preexisting stress favoring movement in one direction rather than another, such as the stress set up by unloading and loading by erosion. These suggestions, though by no means exhaustive, raise problems that invite further research.

The critical test of theories of orogeny is the quantitative one. Is the force competent to move the masses that have been displaced? Can it continue to act during a sufficient time and to a sufficient distance

to produce the observed displacements and compressions? The force here invoked is that with which molecules assume forms adapted to their environment or grow. So far as experiments have been carried in testing it, it appears that the force with which crystals grow is limited only by the crushing strength of the rocks. Of course no greater force could be exerted.

The continuity of effort depends on the persistence of the stimulating heat energy, which seems to be commensurate with the prolonged evolution of terrestrial processes.

The distance to which a given pressure may be transmitted depends on the rigidity of the strut through which it acts. The strut itself may be sheared or crushed, as has happened in the progressive minor thrusting of the Scotch Highland type. The metamorphic stress here postulated is favorably conditioned for distant transmission. Originating in the zone of flow and in a locus where high temperature weakens the opposed shearing strength, it meets initially with low resistances. Strain melting or metamorphism on shearing planes tends to reduce friction. Lubrication of shearing planes by intruded magma has the same effect. These conditions persist in a spherical shell of the globe above which are cooler and more rigid layers. The shell of maximum strength and rigidity lies above the shallowest depth at which an asthenolith is thought to develop—that is, above 30 miles below the surface. According to deductions from the experiments of F. D. Adams on the strength of rocks under pressure, the layer of maximum strength is that which occurs between 5 and 25 miles below the surface, where load has its greatest relative effect on the internal cohesion and friction and where the temperature is not high enough to induce material weakness.[6] This layer may be regarded as the rigid strut, which, when carried forward on the expanding cover of an asthenolith or when sheared by a thrust rising from below, is capable of folding strata in geosynclines or of shearing off the margin of a continental plateau.

Thus, so far as appears from this analysis, the postulated metamorphic stress is quantitatively adequate and favorably located to produce the effects of orogeny.

[6] Bailey Willis: Discoidal structure of the lithosphere. Bull. Geol. Soc. Am., vol. 31, 1920, pp. 249-302.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 40, PP. 589–596 DECEMBER 31, 1929

INFLUENCE OF THE GLACIAL AGE ON THE EVOLUTION OF MAN[1]

BY HENRY FAIRFIELD OSBORN

(Read before Section E of the American Association for the Advancement of Science December 27, 1928)

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PREFATORY NOTE BY THE EDITOR

The following seven papers, which were arranged as a symposium on the centenary of the Glacial theory, constituted the program of the American Association for the Advancement of Science and the Geological Society of America in joint session during the afternoon of December 27, 1928, at the American Museum of Natural History, New York. The papers listed in the symposium bear the following titles:

H. F. Osborn, "Influence of the Glacial Age on the Evolution of Man."

C. A. Reeds, "Weather and Glaciation."

E. Antevs, "Maps of the Pleistocene Glaciations."

R. A. Daly, "Swinging Sealevel of the Ice Age."

W. H. Hobbs, "Climatic Zones and Periods of Glaciation."

F. Leverett, "Glaciations of the Northern Hemisphere."

C. A. Reeds, Base Maps of the World.

[1] Manuscript received by the Secretary of the Society July 25, 1929.
This paper forms part of the symposium on the centenary of the Glacial theory.

The subject for this series of addresses presented itself to Professor Henry Fairfield Osborn, President of the American Museum of Natural History and of the American Association for the Advancement of Science for 1928, while reviewing the work of Louis Agassiz for an address at the unveiling of the Agassiz bust in the Hall of Fame, New York University, New York, March, 1928. In arranging the symposium contributions were solicited from various scientists, but only those noted above were able to submit papers.

As stated by Leverett in his review of the "Pleistocene glaciations of the Northern Hemisphere" the glacial theory took definite form about 1828. The volumes by Charpentier and Agassiz on glacial phenomena aroused widespread interest and study of the evidence in Europe and North America in the decade 1840 to 1850. Renewed interest in the subject developed in the period 1870 to 1900 when attention was focused on the complexity of glacial history in both continents. This resulted in the determination of a well defined series of drift sheets in North America and Europe. In Africa, Asia and South America, however, the extent and complexity of glacial deposits have not been fully investigated.

The papers of the symposium, which follow, deal not only with the history of the glacial theory, but also with a survey of present knowledge and a consideration of some current glacial problems. It may be noted that although much work has been done in unravelling the interlocking problems connected with the advance and retreat of successive Pleistocene glaciations and older glaciations, during the last hundred years, much remains to be done in areal mapping and in the philosophical interpretation of the data before the various glaciations are fully understood.

Introduction by Henry Fairfield Osborn

As an ardent opponent of the evolution theory, Louis Agassiz would be astounded today were he to witness the rapidly accumulating proofs of the influence of his favorite theory of a Glacial age on the evolution of man.

Weakness of the Darwinian Hypothesis of the Ape Ancestry of Man

In the evolution of no other organism is the struggle for existence more potent than in man, especially in the early phases of his career, when he is learning to depend more on intelligence and adroitness than on sheer strength and agility of movement. The weakness of the Darwinian hypothesis, namely, that man branched off from some member

of the anthropoid ape family living in a warm tropical and forested region, lies in the fact that such a region is never known to afford the struggle for existence essential to the development of human intelligence. On the contrary, it puts intelligence asleep. Even today all human types as well as all anthropoid ape types living in warm tropical and forested regions are either stationary or actually retrogressive in intelligence. Our present knowledge of the Glacial Age weighs against Darwin's hypothesis of our ape ancestry.

Climatic Changes affecting Man's Evolution

As shown in figures 1, 2, and 3, the 1,250,000-year story of the evolution of man opens with Europe as a warm forested region of south temperate climate inhabited by a rich assemblage of large African mammals, such as the hippopotamus, the rhinoceros, and the southern mammoth. Toward the close occurs the extreme climatic severity of Glaciation IV, with the extinction of this entire warm fauna and invasion of a subarctic and tundra fauna of the woolly rhinoceros, the woolly mammoth, and the steppe antelopes and horses. During this time human intelligence awoke from its long slumber. Then followed gradually the extinction and retreat to the north of this cold fauna and entrance of the north temperate mammals, which covered Europe until exterminated by man. The environmental condition of these successive archeologic, racial, and climatic phases is clearly shown in figures 1, 2, and 3, prepared by Dr. Reeds and myself in 1922 and now brought up to the date of recent discoveries.

The Osborn Dawn-man Hypothesis

It is such observations and reflections as these which led me in 1923 to abandon the anthropoid ape and forest-living hypothesis of Darwin and substitute a new hypothesis of my own, namely, that the human stock branched off from the anthropoid ape stock during the period of the first onset of dryer and even semi-arid conditions in certain of the higher plateau regions of the earth. It is the dryer plains and plateau regions chiefly which gave rise to bipedal types with narrow feet, as distinguished from quadrupedal and arboreal types with rather broad spreading feet and limb-grasping hands.

This newer synthesis of human origin, however, requires geologic and paleogeographic support. In brief, it must be solved through a synthesis of evidence coming from every source, and no period of the earth's history requires such a broad and exacting synthesis in relation to the evolution of man as the Glacial age, which we owe to the original observations of Charpentier and the prophetic vision of Louis Agassiz.

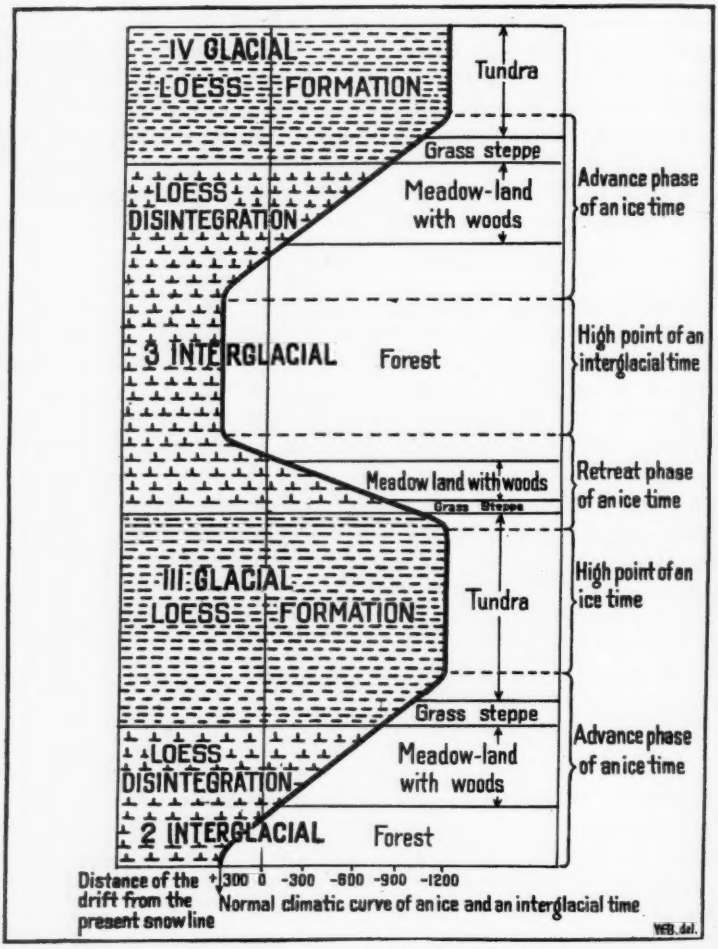


FIGURE 1.—*Normal climatic Curves of Glacial and Interglacial Times.*

After Soergel, 1919, modified by C. A. Reeds, 1921.

In several of the loess formations of many parts of Europe are discovered a succession of flint-making camps by which both the loess and the flints can be precisely dated. The theoretic succession in descending order is as follows:

IV. Glacial and postglacial time, youngest loess formation, tundras and grass steppes.

3. Interglacial phase, loess disintegration, moist climate, forests, meadow lands, and woods.

III. Glacial phase, second loess formation, tundras to the north, grassy steppes to the south.

2. Interglacial phase, loess disintegration, meadow lands, woods, and forests.

Compare upper portion of figure 3.

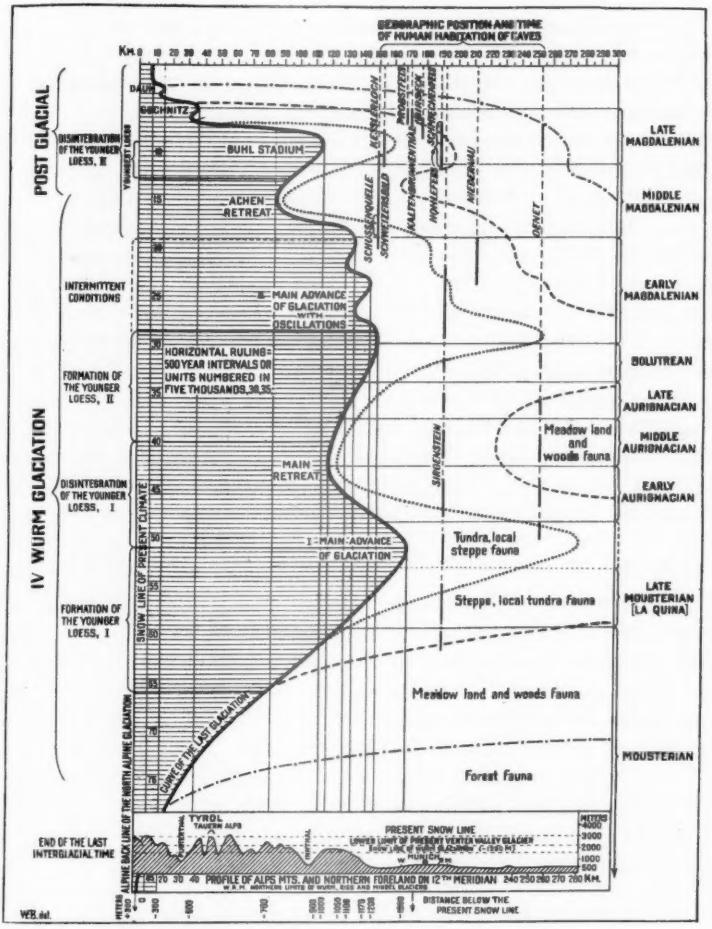

GEOGRAPHIC POSITION AND TIME OF HUMAN HABITATION OF CAVES
POST GLACIAL
IV WURM GLACIATION
DISINTEGRATION OF THE YOUNGER LOESS, II
INTERMITTENT CONDITIONS
FORMATION OF THE YOUNGER LOESS, II
DISINTEGRATION OF THE YOUNGER LOESS, I
FORMATION OF THE YOUNGER LOESS, I
YOUNGEST LOESS
BÜHL STADIUM
ACHEN RETREAT
MAIN ADVANCE OF GLACIATION WITH OSCILLATIONS
HORIZONTAL RULING = 500 YEAR INTERVALS OR UNITS NUMBERED IN FIVE THOUSANDS, 30,35
MAIN RETREAT
MAIN ADVANCE OF GLACIATION
SNOW LINE OF PRESENT CLIMATE
ALPINE BACK LINE OF THE NORTH ALPINE GLACIATION
CURVE OF THE LAST GLACIATION
LATE MAGDALENIAN
MIDDLE MAGDALENIAN
EARLY MAGDALENIAN
SOLUTREAN
LATE AURIGNACIAN
MIDDLE AURIGNACIAN
EARLY AURIGNACIAN
LATE MOUSTERIAN (LA QUINA)
MOUSTERIAN
Meadow land and woods fauna
Tundra, local steppe fauna
Steppe, local tundra fauna
Meadow land and woods fauna
Forest fauna
END OF THE LAST INTERGLACIAL TIME
TYROL
PRESENT SNOW LINE
PROFILE OF ALPS MTS. AND NORTHERN FORELAND ON 12TH MERIDIAN
DISTANCE BELOW THE PRESENT SNOW LINE
WEB. del.

FIGURE 2.—*Graphic Presentation of the last Alpine (Würm) Glaciation.*

Detail of upper portion of Figure 3.

After W. Soergel, 1919, with additions and modifications by Chester A. Reeds, 1921. This illustration indicates the connection of the last Alpine glaciation with the younger and youngest loess and its distribution; also, the timely succession of different mammal faunas and the position and series of paleolithic cultures from Mousterian to Magdalenian. In this glaciation the flint archeology is most varied and can be most closely correlated, and extremely precise results are obtainable. Compare figure 1; also uppermost portion of figure 3.

In 1922 Osborn and Reeds [2] summed up such synthesis by calling on no less than twelve different branches and sub-branches of science in the fields of astronomy, oceanography, meteorology, geology, paleontology (vertebrate and invertebrate), archeology, and anthropology. As the Glacial age and Quaternary time were passing, these *twelve* or more bases of synthesis were constantly interrelated; consequently each makes its contribution to chronology. Successive attempts to establish a consistent chronology of the Northern Hemisphere during the Glacial age by Geikie, Penck and Brückner, Depéret, de Geer, as summarized by Osborn and Reeds in 1922, appear in the adjoining table (figure 3), which is quite profoundly modified, in comparison with the Osborn-Reeds table of 1922, by very recent discoveries in the synthesis of mammalian and human paleontology.

Whereas between 1914 and 1922 the famous Trinil man of Java was regarded as of upper Pliocene age, while the Piltdown man of Sussex was considered of lower Pleistocene age, it now appears almost certain that the Trinil man of Java is of middle Pleistocene age, while the Piltdown man of Sussex may prove to be as ancient as upper Pliocene time.

Changes in the Osborn-Reeds archeological Column of 1922

Similarly, the changes made in the archeological column of the Osborn-Reeds correlation of 1922 reproduced herewith (figure 3) are no less profound. In this matter I had the privilege of recently consulting with Professor Penck, who has abandoned his archeologic or flint culture correlation of the great Penck-Brückner monograph of 1908-1921 and substituted an archeological sequence in which the early Chellean and Chellean flints are placed way back in first and second interglacial time. Not only this, but well-shaped flints difficult to distinguish from the Chellean type of the River Somme have now been positively located in the beds of upper Pliocene age in East Anglia by Reid Moir.

The mental Development of Man

Thus the Glacial age has ceased to be the theater of the *origin of man*, which no longer belongs in Quaternary time, but is pushed back into Tertiary time. But, while surrendering to the Tertiary environment the honor of presiding over the origin of man and man's passage into the bipedal mode of progress, the Quaternary may now more strongly than ever lay claim to the greater honor of developing the intelligence

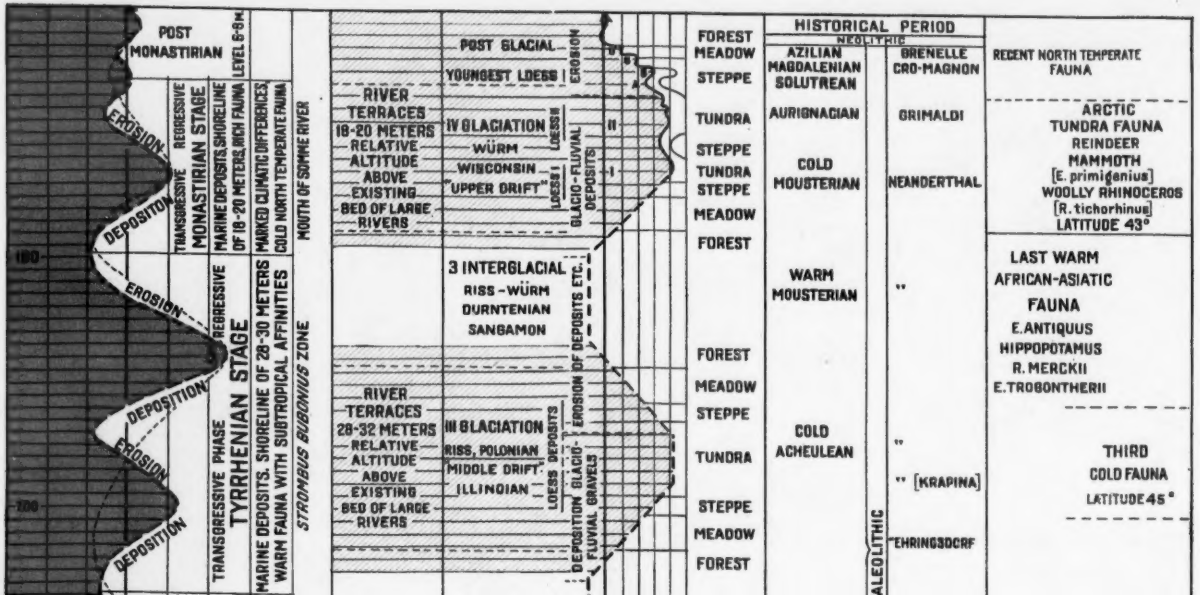
[2] Henry Fairfield Osborn and Chester A. Reeds: "Old and new standards of Pleistocene division in relation to the prehistory of man in Europe." Bull. Geol. Soc. Amer., December 30, 1922.

of man; and the chief theater of this intelligence was not only the Northern Hemisphere, but in those portions of the hemisphere which were exposed to the greatest vicissitudes of climate. The races, like the Trinil race of Java and the negroid races of Africa, which sought the more genial life of the southern tropical forests and plateaus, remained stationary. On the contrary, the races which faced the sterner conditions of the regions contiguous to the great northern waves of ice and the oft-repeated sequence of dryer and moister climates, compelling the repeated northward and southward migrations of the mammals, are those in which civilization had its birth.

However, when the first actual evidence of man is discovered in closing Pliocene time, the climatic and environmental conditions of life on the 40th parallel are mild and easy and man, in Europe at least, shows an extremely prolonged period of partly arrested development owing to the relaxation of the struggle for existence, indicated by the Cromerian to the Mousterian industries (figure 3). This period of arrested development lasted through the first, second, and third glacial onsets, during which western Europe was populated solely with the low-browed races of Neanderthal type. The first three glacial epochs pass away, while there are no very marked or profound changes in the mammalian life of western Europe nor in the advance of man himself. The fourth glacial epoch changes all this and puts the older Neanderthal races to a very severe test, culminating in the arrival of new higher races, as we believe, from the central plateau regions of Asia. This is the second great application of the principle of the struggle for existence to the evolution of man. Throughout this long period, from the close of the Pliocene until the present day, *it may be said that we are chiefly dependent on glacial phenomena not only for the chronology of man, but for an adequate theory of the causes of the mental and spiritual evolution of man.* Finally, in central Asia the pulse of the Glacial age is felt in humid conditions which prevailed in the Desert of Gobi between twenty-five and forty thousand years ago, favoring the rapid spread and multiplication of the dune-man race and culture, as discovered and described by Andrews, Nelson, and Berkey of the Central Asiatic Expeditions.

Conclusion

In conclusion it may be said without exaggeration that our rapidly advancing knowledge of the anthropology of the Stone Age is largely due to the triumphant applications of the glacial theory of Charpentier and Agassiz, which is now celebrating its centenary.


POST MONASTIRIAN
EROSION
DEPOSITION
EROSION
REGRESSIVE
TRANSGRESSIVE
MONASTIRIAN STAGE
MARINE DEPOSITS, SHORELINE OF 18-20 METERS, MICH FAUNA
LEVEL 6-9 M.
MARKED CLIMATIC DIFFERENCES, COLD NORTH TEMPERATE FAUNA
MOUTH OF SOMME RIVER
180
DEPOSITION
EROSION
REGRESSIVE
TRANSGRESSIVE PHASE
TYRRHENIAN STAGE
MARINE DEPOSITS. SHORELINE OF 28-30 METERS
WARM FAUNA WITH SUBTROPICAL AFFINITIES
STROMBUS BUBONIUS ZONE
200
DEPOSITION
POST GLACIAL
YOUNGEST LOESS
EROSION
RIVER TERRACES 18-20 METERS RELATIVE ALTITUDE ABOVE EXISTING BED OF LARGE RIVERS
IV GLACIATION
WÜRM
WISCONSIN
UPPER DRIFT
LOESS II
LOESS I
GLACIO-FLUVIAL DEPOSITS
II
I
3 INTERGLACIAL
RISS-WÜRM
DURNTENIAN
SANGAMON
EROSION OF DEPOSITS ETC.
RIVER TERRACES 28-32 METERS RELATIVE ALTITUDE ABOVE EXISTING BED OF LARGE RIVERS
III GLACIATION
RISS, POLONIAN
MIDDLE DRIFT
ILLINOIAN
LOESS DEPOSITS
EROSION
DEPOSITION
GLACIO-FLUVIAL GRAVELS
2
FOREST
MEADOW
STEPPE
TUNDRA
STEPPE
TUNDRA
STEPPE
MEADOW
FOREST
FOREST
MEADOW
STEPPE
TUNDRA
STEPPE
MEADOW
FOREST
HISTORICAL PERIOD
NEOLITHIC
AZILIAN
MAGDALENIAN
SOLUTREAN
AURIGNACIAN
COLD
MOUSTERIAN
WARM
MOUSTERIAN
COLD
ACHEULEAN
PALEOLITHIC
GRENELLE
CRO-MAGNON
GRIMALDI
NEANDERTHAL
"
"
"
[KRAPINA]
EHRINGSDORF
RECENT NORTH TEMPERATE FAUNA
ARCTIC
TUNDRA FAUNA
REINDEER
MAMMOTH
[E. primigenius]
WOOLLY RHINOCEROS
[R. tichorhinus]
LATITUDE 43°
LAST WARM
AFRICAN-ASIATIC
FAUNA
E. ANTIQUUS
HIPPOPOTAMUS
R. MERCKII
E. TROGONTHERII
THIRD
COLD FAUNA
LATITUDE 45°

MILAZZIAN STAGE
TRANSGRESSIVE PHASE
REGRESSIVE PHASE
MARINE DEPOSITS. SHORELINE OF 55-60 METERS
WARM FAUNA, LESS WARM THAN TYRRHENIAN STAGE
EROSION
DEPOSITION
EROSION
MEAN LEVEL
DEPOSITION
EROSION
HORIZONTAL RULING
200
400
600
800
STAGE
LINE OF 80-100 METERS
TEMPERATE FAUNA WITH
THE MEDITERRANEAN
REGRESSIVE PHASE
RIVER TERRACES
55-60 METERS
RELATIVE ALTITUDE
ABOVE EXISTING BED OF LARGE RIVERS
I GLACIATION
MINDEL
SAXONIAN
KANSAN
"OLD DRIFT"
LOESS DEPOSITS
DEPOSITION OF FLUVIAL GRAVELS
EROSION OF DEPOSITS AND STREAM BED
REMNANTS OF TERRACES
2 INTERGLACIAL
MINDEL - RISS
TYROLIAN
YARMOUTH
1 INTERGLACIAL
REMNANTS OF TERRACES
FOREST
MEADOW
STEPPE
TUNDRA
STEPPE
MEADOW
FOREST
EARLY
CHELLEAN
LATE
CHELLEAN
WARM
ACHEULEAN
PALEOLITHIC
HEIDELBERG
WARM
AFRICAN-ASIATIC
FAUNA
E.MERIDIONALIS
E.ANTIQUUS
SECOND
COLD FAUNA
LATITUDE 48°
WARM
AFRICAN-ASIATIC
FAUNA
E.TROGONTHERII
E.ANTIQUUS
R. MERCKII
HIPPOPOTAMUS
EHRINGSDORF

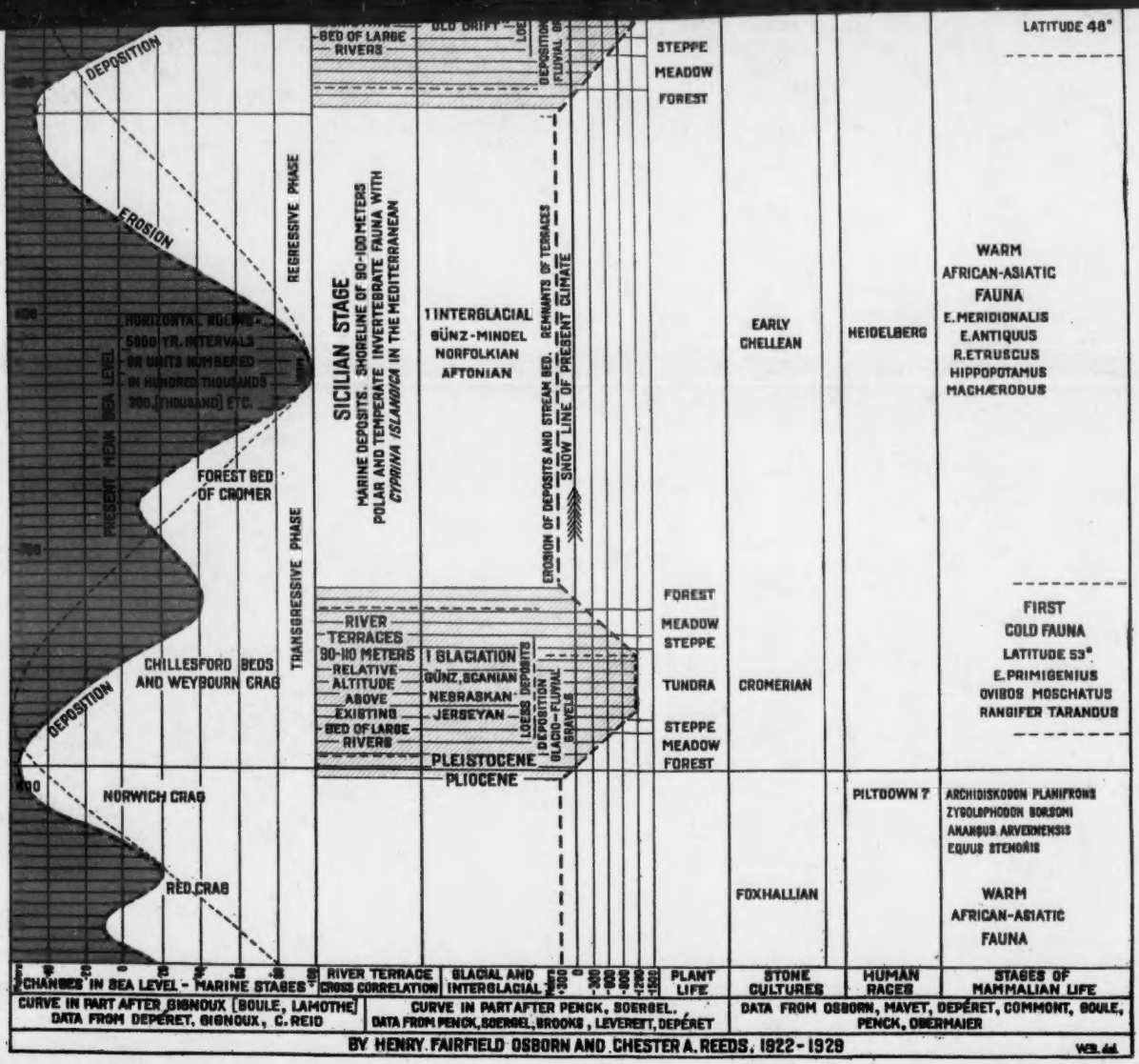


FIGURE 3.—*The modified Osborn-Reeds Correlation Table of 1922.*

Continental subsidences and marine transgressions in dark blue. Alternating glacial advances in light blue. Relative time intervals between the four glacial advances as estimated by Penck-Brückner, 1908-1921.

This table was modified by the recent observations of Penck, Reid Moir, Osborn, and others as to the appearance and succession of the stone cultures and human races. All the stone cultures, namely, Acheulean, late Chellean, Chellean, early Chellean, and Cromerian, have now been traced back to earlier phases of Pleistocene time than was formerly believed. By Reid Moir the Cromerian flint industry of the Forest Bed of Norfolk is now regarded as of the same age as the early Chellean or pre-Chellean. Reid Moir has recently discovered flint of the Chellean kind even *below* the Red Crag which is true upper Pliocene.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 40, PP. 597-630 DECEMBER 31, 1929

WEATHER AND GLACIATION[1]

BY CHESTER A. REEDS

(Read before Section E of the American Association for the Advancement of Science, December 27, 1928)

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INTRODUCTION

Weather as it affects glaciation is a subject which has been under observation during the past century. Remnants of the last glaciation still exist in Greenland, Antarctica, and on some of the islands of the polar regions and in the high mountain fastenesses of the temperate and tropical zones. Weather conditions are modifying these ice-masses; in fact, the variability of the weather causes glaciers to grow at certain times and wane during other periods. The changes that are going on today are apparently similar to those that took place during past ages.

There is a distinction between weather and climate. Climate is the average of normal conditions of the atmosphere, while weather constitutes the variations from the normal. Weather changes are of a day-to-day occurrence. When averaged for the year and for longer periods, they yield differences which make the weather of one year vary from that of another, as well as for groups of years.

During the last decade a few meteorologists have correlated weather changes with variations in solar radiation. This correlation has been

[1] Manuscript received by the Secretary of the Society, December 21, 1929.

specially emphasized by H. H. Clayton in his volume, "World Weather," 1923. The correlation of changes in glaciation with solar radiation variations has been mentioned by various scientists, but it has not been discussed in the light of recent developments. In this paper special application of these changes to glacial deposits at Haverstraw, New York, and New Haven, Connecticut, will be made.

The Conditioning of Ice-Sheets and Glaciers

There are two opposing factors which modify ice-masses, namely, nourishment and depletion. Nourishment consists primarily of snowfall, hoar frost, rime, glaze, sleet, and needles, or spiculæ, sometimes referred to as "frost snow" or "polar snow." According to Antevs (1929), depletion occurs through melting, evaporation, discharge of bergs, etcetera. Melting, which is the most important agent, takes place through high temperature, insolation, and to a minor degree from rain, air, wind, and water. Glaciers advance after heavy winter precipitations followed by low summer temperatures and cloudiness. They retreat following slight winter snowfalls, high summer temperatures, and clear sky.

It has been said that the cause of the principal variations in the present size and condition of glaciers in Alaska is due to variations in altitude, in latitude, in precipitation, and in direction of slope (Tarr and Martin, 1914). Fluctuations in Alpine glaciers have been traced back to about 1600 A. D.; in Norwegian glaciers, to about 1700 A. D. Yearly measurements were begun on the Rhone Glacier in 1874 and on other glaciers in various parts of the world since 1894. Weather changes are not immediately recorded at the terminal end of an ice-mass, since glaciers vary as to size of the névé field, depth of the catchment basin, width of the fern field, length of the ice-tongue, et cetera. For example, small glaciers in the Alps began to advance in 1909 and 1910; medium-sized glaciers in 1912 and 1913, while long valley glaciers, such as the Allain, did not advance until 1920, when it moved forward 120 feet, and a greater amount in 1921. The variability of the weather thus causes glaciers to advance or retreat, but not all at the same time; for, being of different sizes, their respective masses, as well as other factors, tend to govern their movements.

Some Properties of Ice

Under the influence of heat, ice behaves as most solids do, contracting when cooled, expanding when heated. As regards the evaporation of ice, it was shown by Barnes and Vipond in 1909 that it goes directly into vapor without passing through a preliminary liquid phase. The

melting point of ice is lowered by increase of pressure. The rate at which this occurs is 0.0075 degrees centigrade for every atmosphere of pressure. This fact was theoretically predicted by James Thomson in 1849 and demonstrated by Sir W. Thomson (Lord Kelvin) in 1850.

Although there is no rise of temperature accompanying the melting of ice, a definite quantity of heat is absorbed, namely, about 80 calories per gram, or 78.818 thermal units. The same amount of heat is evolved when water becomes ice—that is, the amount of heat required to convert ice into water, or *vice versa*, would raise the same amount of water through 80 degress centigrade. This is the latent heat of fusion of ice or the latent heat of water. Because of this fact, ice is the most difficult of all solids to melt, as regards the amount of heat energy required to be put into it in order to effect fusion, and water the most difficult liquid to freeze of all substances, owing to the relatively large amount of the latent heat needed. It is fourteen times as great as for lead and twenty-eight times as great as for mercury.

The temperature at which water reaches its maximum density is 39.2 degrees Fahrenheit (3.945 degrees centigrade), according to the researches of Joule and Playfair. When cooled below this temperature water expands instead of contracting, and the expansion goes on to the total extent of one-ten-thousandth of its bulk, until freezing occurs, at 32 degress Fahrenheit (0 degress Centigrade), when there is a sudden expansive leap of nearly a tenth of the whole volume of the water as it freezes to form ice.

The x-ray study of ice crystals by Sir William Bragg (1925) shows that ice contains an open hexagonal lattice structure consisting of four molecules of water. This lattice structure reveals why ice can be melted under pressure and how it is possible for water (with the molecules closely compressed) to occupy less space than ice. It also accounts for the sudden and relatively enormous expansion which occurs when water freezes. On becoming ice, the water has increased in bulk by 9 per cent, and this increase occurs instantaneously and with enormous, well-nigh irresistible, force. It also explains why ice is lighter than water and why ice floats on lakes, rivers, and the open sea with about one-tenth of its volume above water level.

The fresh water of lakes continues to contract with increasing cold. The surface waters, being colder, and thus heavier, sink, and the warmer waters from the bottom rise to the surface. The convection currents thus set up continue until all of the water in the lakes has been reduced to the maximum density of water, after which the circulation stops, for the surface waters, when cooled to lower temperatures, remain on top

and grow steadily colder until they suddenly freeze at 32 degrees Fahrenheit (0 degrees Centigrade).

Solar Radiation Variations

The sun's rays supply nearly all of the heat of the earth's surface. They affect not only the weather, but also insolation and temperature, two of the agencies conditioning ice-masses; hence a brief consideration of solar radiation is important in discussing weather and glaciation.

In 1837 Pouillet invented the pyrheliometer, with which he endeavored to measure the heat of the sun. Violle, Crova, Chowlson, and the Angströms followed him and increased the knowledge of the subject. Langley invented the bolometer for studying the selective absorption and the scattering of light in the atmosphere. With this instrument he measured, during 1902, 1903, and 1904, the solar radiation, corrected for atmospheric influence, and announced that the intensity of solar radiation is subject to irregular variations due to conditions in the sun itself.

More recently Dr. C. G. Abbot, Secretary of the Smithsonian Institution, has improved the instruments and methods of Langley and determined the mean of the "solar constant" to be 1.938 calories per minute per square centimeter. Solar radiation is subject to variations which, although slight, are important. The value of the "solar constant" at a given time may differ from the mean. The highest monthly mean for the years 1918 to 1929 was 1.969 for September, 1921; the lowest, 1.912 for July, 1922, giving a range of 0.057, or 2.9 per cent. The highest yearly mean for the same period was 1.952 for 1921, and the lowest 1.927 for 1922, or a range of 1.3 per cent, according to solar constant values supplied by Dr. Abbot in a personal communication of November, 1929.

The "solar constant" variations for the period 1905 to 1929, inclusive, have been arranged in the form of a graph, figure 1, by entering the yearly mean fluctuations on the ordinates and the years on the abscissa. This is the same method and grid used in figures 2 to 13 for the varved clays. The value, 1.900, is equivalent to the base line. The original drawing has been reduced one-half during publication.

According to Wolfer's sun-spot numbers, there was a maximum of spots in February, 1907, a minimum in May-June, 1913; a maximum in August, 1917, a minimum in August, 1923, and a maximum in July, 1928. These figures, when compared with the solar radiation values, as noted in figure 1, show a relation between them in the eleven-year cycle. Abbot (1929) states that the solar radiation rises to a maximum with medium sun-spot numbers and declines thereafter as sun-spot

numbers increase. Furthermore, superposed on the sun-spot influence variation there appears to be three pulses of regular periods of about 25, 15, and 11 months respectively, and of amplitudes which are large enough, when combined in similar phase, to nearly overpower the maximum sun-spot effect on the solar-constant values.

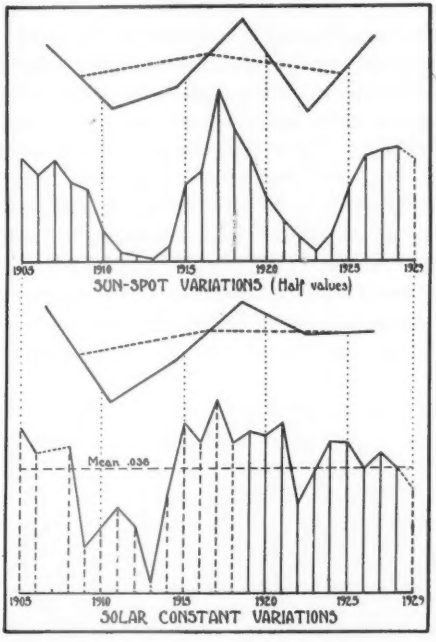

FIGURE 1.—*Graphs of solar Constant and Sun-spot Variations 1905 to 1929.*
Curves smoothed by taking the mean of successive four (solid line) and eight (dotted line) years appear above each graph. In the solar-constant graph the vertical lines have been dotted where the data were incomplete for the year. Data from Dr. C. G. Abbot, November, 1929.

The 1905 to 1929 monthly averages of sun-spots show little apparent relation with that of solar radiation. The yearly means, however, 1905-1929, exhibit a more evident comparison. A closer resemblance between the two is secured when the three to four year oscillations in solar radiation, which are not appreciable in sun spots, are smoothed by means of four, and further smoothed by taking the means of each consecutive two means, figure 1, as was done by Clayton (1923).

According to Abbot (1926), the intensity of solar radiation is expected to increase when sun spots are numerous. However, when an individual sun spot crosses the central part of the sun a depression in solar radiation

is usually noticeable, which is attributed to a sort of cloudiness over each sun-spot group. The resulting depressing effect may exceed one of increased radiation. Thus it may be said that there is a real relation, though not a very close one, between sun spots and solar radiation.

Effects of Atmospheric Opacity

The radiation from the sun which reaches the earth is considerably reduced by the opacity of the earth's atmosphere. According to H. N. Russell (1926), only about 70 per cent of the initial solar radiation gets through to sealevel when the sun is at the zenith and the air is free from dust and clouds. The opacity increases as the sun approaches the horizon, due to the greater distance the rays have to travel through the atmosphere and the loss of the shorter rays by diffraction. The only satisfactory way of dealing with these variations is to measure with the spectrobolometer the energy received when the sun is at various altitudes. Each different wave-length has to be measured separately to determine the depletion for each and the various amounts summed up to find the total solar radiation outside the atmosphere. The process is definite, but laborious.

Normal opacity of the air may be much increased by the presence of four by-products, which may be regarded as factors that affect solar radiation, namely, water vapor, carbon dioxide, ozone, and dust. Water vapor has the most thermostatic influence. In tropical regions, where the humidity is high, nearly half of the sun's heat is absorbed by a cloudless sky. A cloud surface may reflect more than 70 per cent of the sun's rays and absorb a large part of the remainder, while a canopy of dense clouds may permit only a small part of the sun's radiant energy to reach the earth. Since carbon dioxide and ozone are present in the air in very small quantities, their influence is subordinate to that of water vapor. Ozone probably absorbs some of the solar radiation, since laboratory experiments tend to show that it does.

Dust in the air causes a decrease of the solar radiation reaching the earth. When dust is blown to heights of ten to fifty miles by volcanic eruptions—that is, into the isothermal region or stratosphere—the direct solar radiation at high sun may be reduced as much as 20 per cent, as was noted following the Katmai eruption of June 6, 1912. Not all great volcanic eruptions decrease the surface temperaures of the earth, but only those that drive a lot of dust into the isothermal region of the atmosphere. Volcanic eruptions during historic times and their influence on solar radiation and the weather have been traced. Such eruptions may have accounted for many of the great changes in the

weather that the earth has experienced. W. J. Humphreys has accepted this view and formed his vulcanism theory of glaciation.

Humphreys (1920) considers the average size of the volcanic dust particles in the stratosphere to be 1.85 microns. He calculates that it would require about one year for such particles to fall from an elevation of 35 kilometers to the lower limit of the stratosphere, which has an elevation above sealevel of 17 kilometers in tropical latitudes, 11 kilometers in middle latitudes, and 6 kilometers in polar regions. He considers the finest volcanic dust, which may have reached an altitude of 40 to 80 kilometers following the eruption of Krakatoa in 1883 and Katmai in 1912, and which encircled the earth a number of times, to have taken two and one-half to three years to reach the base of the stratosphere, or upper cloud level. He estimates that the total quantity of volcanic dust required to cut down the intensity of the direct solar radiation by 20 per cent to be only the 174th part of a cubic kilometer, or the 727th part of a cubic mile, assuming that the particles are spherical. Since the particles are more or less flat, it is probable that not more than the 1,500th part of a cubic mile, or the 350th part of a cubic kilometer, is needed to reduce the intensity of direct solar radiation 20 per cent. This amount, if indefinitely continued, he concludes, would be capable of producing an ice age.

With the particles all being 1.85 microns in size, he calculates that the volcanic dust is some thirtyfold more effective in shutting out solar radiation than it is in keeping terrestrial radiation in. This is because radiation, both solar and terrestrial, is simply scattered by such small particles and scattered in proportion to the inverse fourth power of the wave-length. Since the ratio of solar wave-length to terrestrial wave-length is, roughly, 1 to 25, and the ratio to their fourth powers as 1 to 39×10^4, it follows that the interception of outgoing radiation by the very finest, and therefore most persistent, dust is wholly negligible in comparison with its interception of incoming solar radiation.

Solar Radiation and the Weather

Since 1915 H. H. Clayton, retired, formerly chief forecaster for Argentina, has been using the averages of groups of high, medium, and low solar radiation values of the Astrophysical Observatory of the Smithsonian Institution in attempting to correlate them with atmospheric changes on the earth. He has compared these means with the means of temperature and pressure variations scattered over the earth and attained results which show systematic changes which seem difficult to explain on any other grounds than a real relation.

The more usual solar fluctuations are irregular and occupy a few days or weeks. Clayton (1923) obtained the best comparisons of day-to-day fluctuations by averaging the values of each phenomenon in groups of five, ten, or more days, after allowing, in some instances, an interval of three days for a lag in the effect. He noted a tendency to short-period variations in 3.5, 7, and 13.5 days, which he attributed to successive outbreaks of faculæ on the solar surface. Traces of similar tendencies in the weather were also observed.

Clayton also noted solar radiation values of similar kind at intervals of about 11 and 16 days, which he correlated with the movement of heated gases from one side of the sun to the other. These heated gases are associated with solar faculæ. He observed similar variations in temperature at Buenos Aires in 1921.

In addition to the day-to-day variations, Clayton has averaged those for monthly, yearly, and longer periods and established an intimate relation between them and those of the weather. He observes that the complexity of the weather changes arise from complexities of solar radiation in which changes of short period are mixed with progressively longer waves of change going up into years and centuries.

Clayton has shown that with an increase of solar radiation the temperature rises and the pressure falls in equatorial regions and is immediately followed by a rise of pressure and a fall of temperatures in temperate regions, reaching a maximum between latitudes 40 and 60 degress north and south. Over the oceans, in still higher latitudes, 60 degrees to 70 degress, the relation is again direct, as in the tropics—that is, the temperature rises and the pressure falls with increase in solar radiation. From the region of maximum rise of pressure, a wave of returning pressure starts toward the Equator with a velocity inversely proportional to the length of the solar cycle and drifts eastward with the eastward drift of the atmosphere, dying out in low latitudes. This effect is true, whether the increase in solar radiation be for a few days, for months, for years, or for longer periods. With the solar radiation below normal, the effects for the different regions for the same time of year are the reverse of those when there is an equivalent excess of solar radiation.

As noted by Clayton, the monthly means of solar radiation and those of temperature and pressure show that with an increase in intensity of solar radiation the maxima of pressure form over the coldest parts of the temperate zones, which are the continents in winter and the oceans in summer. The more intense the radiation, the farther north and south are these maxima of pressure formed. The abnormal distributions of temperature and precipitation are intimately related to the

distribution of pressure. Thus the centers-of-action move north and south of their mean position with the varying intensities of solar radiation. There is a lag in the solar effect near the centers-of-action proportional to the duration of the solar change. In general the lag is about one-twelfth of the length of the interval from maximum to maximum or minimum to minimum. The lag may vary from a few hours to a year, depending on the duration of the effect.

The year-to-year variations in solar radiation are shown by Clayton to be connected with year-to-year variations in rainfall and river heights in North America, South America, and Australia. He also observes that the solar measurements clearly indicate the existence of a three to four year change in solar radiation, which is reflected in a three to four year change in pressure, rainfall, etcetera. This he attributes to a variability in the intensity and amount of faculæ on the surface of the sun.

Clayton's studies of the effect of maximum and minimum sun-spot periods on the weather show that the pressure is lower at the time of maximum sun spots in the equatorial zone, especially in the humid regions, at all times of the year. The differences of pressure are, however, much less than in the case of the monthly means. Koppen has shown that the mean temperature of the surface air over the globe was lower at sun spot maximum than at sun spot minimum. Although much has been written concerning the effect of sun spots on the weather, investigators agree that weather conditions are far more variable than sun-spot numbers.

Records of Weather Changes Extending over Many Years

Weather changes extending over long periods of time are reflected in the annual growth rings of trees (Douglass, 1909, 1914, 1919, 1928, 1929; Huntington, 1914). Harris (1926), in considering the correlation between sun-spot numbers and tree-growth, concludes that the coefficients indicate a low positive correlation between them, but the relationship is by no means so intimate as many writers imply.

The best-preserved records of weather affecting glaciation are found in the aqueo-glacial deposits of Pleistocene age, which preserve seasonal, annual, and longer period variations. The deposits are commonly known as laminated or varved glacial clays.

These laminated glacial clays, which record the annual retreat and ablation of the last continental ice-sheet, have been studied, during the last twenty years, in North America, Sweden, Finland, Iceland, Argentina, and the northwestern Himalaya Mountains of India. While the primary object of the investigation has been the establishment of a

geochronological time scale, with the varve or year as the unit of measurement, a study of the variations in thickness preserved in the seasonal and annual layers is of special interest, since it involves weather changes which affected the melting of the ice during its retreat.

The material composing the varved clays was brought directly from the melting ice by subglacial streams and deposited in fresh or slightly brackish water lying in front of the receding ice-mass. The mud was brought into the lake during the annual melting period—that is, the summer months. The quantity delivered was in all probability proportional to the quantity of ice that underwent melting. It apparently was not directly influenced by the nourishment of the ice as was the retreat of the ice-front. Thick varves thus signify a long period of warm summer weather; thin varves imply short summers, with cold and foggy weather. The varve graphs which have been published, showing summer and winter thicknesses, record fairly accurately the yearly variations of the amount of summer temperature.

The lamination of the clay sediments postulates a strict periodicity, not only in the melting of the ice and the deposition of the "summer" layer, but a pause of several months, during which time the supply of sediment is interrupted and the fine clay particles, which remain suspended in the fresh-water lakes following the summer influx, have had sufficient time to settle to the bottom and form the dark "winter" layer, consisting of pure clay. No phenomena other than seasonal variation—that is, the alternation of summer and winter—meets this postulate. Varved clay sediments produced by this seasonal variation are being deposited now in Lake Louise, Alberta, Canada (Johnston, 1922).

In addition to the seasonal variation, there is an annual or varve variation in which changes in thickness occur from year to year. The thickness of the varves usually varies in different basins from a few millimeters to three or four centimeters, sometimes more. For instance, the varves in the Hudson River basin at Haverstraw, New York, average 35 millimeters (1.38 inches) in thickness, while those in the Quinnipiac Basin, near New Haven, Connecticut, average 23.24 millimeters (0.92 of an inch). The relative differences as well as other structural features, however, remain constant over wide regions as well as over widely scattered occurrences. Thus it is possible to identify and correlate the varves in separate sections.

With samples of the material in hand the correlation is often effected by a comparison of the variations in thickness, color, or peculiar lamination of successive varves or groups of varves. The seasonal and yearly variations are also noticeable when measuring the thickness of the

sediments in the field on strips of paper. Their relative values, however, are made more apparent when plotted graphically, according to a method initiated by Gerard de Geer, of Sweden, in 1906. The diagram consists of a horizontal base line from which arise a number of vertical lines spaced one-half centimeter apart. These equally spaced lines on the abscissa are numbered to represent the varves or years. The thickness of the successive varves from the bottom upward are entered as ordinates from left to right on the successive vertical lines and the tops united with one another to make them stand out more effectively. A comparison of such diagrams representing different sections brings out whether they are common varves and how they are related to one another (figure 2).

Varved clays are extensively represented in the Pleistocene epoch (De Geer, 1910, 1912, 1921, 1926, 1927*a*, 1927*b*; Antevs, 1922, 1925, 1928; Norin, 1927; Reeds, 1926, 1927; Sauramo, 1923, 1929; Sayles, 1919). They are also represented in glaciations older than the Pleistocene (Antevs, 1925; Reeds, 1923; Sayles, 1914; Schuchert, 1914; Süssmilch and David, 1919).

Fluctuations in Haverstraw and New Haven Varved Clays

In order to investigate the possible relation between varved clays, glaciation, and weather, the laminated clays at Haverstraw, New York, and New Haven, Connecticut, have been measured, correlated, and specially diagramed. The Haverstraw clays extend along the west bank of the Hudson River from a mile south to two miles north of the town and reach inland one-half mile from the river front. These clays vary in thickness from 50 feet on a 60-foot terrace facing the Hudson River in west Haverstraw to more than one hundred feet in the low plain bordering the river bank. The New Haven clays occur in the low-lying Quinnipiac River valley, in the eastern portion of the city.

The varves in the Haverstraw clays were measured, correlated, and diagrammed by Chester A. Reeds and Ernst Antevs, working intependently. The Reeds diagram of 736 varves was shown and accompanied by abstracts at the Cleveland, 1927, meeting of the Geological Society of America, while Antevs' Haverstraw curve appeared in March, 1928, in his book, "The Last Glaciation," published by the American Geographical Society, Research Series No. 17, as graphs marked New Haven A1, B1, plate I; A2, B2, A3, B3, A4, plate II. The New Haven varved clays, which Antevs correlates with Haverstraw, also appear diagramed and described in this report as graphs labeled New Haven, C2, C3, plate II.

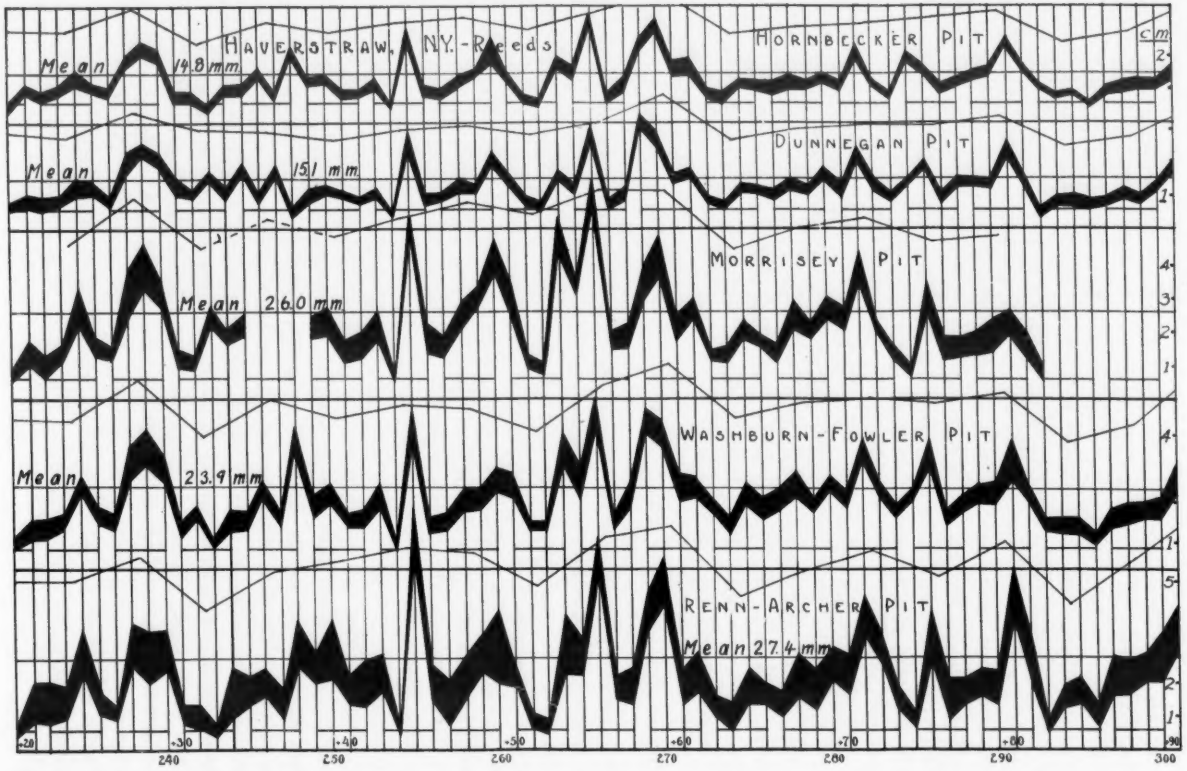

FIG. 2.—*C. A. Reeds' Correlation of 70 Varves occurring in Five separate Clay-pits at Haverstraw, New York.*

Thickness of winter layers indicated by black shading. The smoothed curve appearing above each of the five graphs has been developed by averaging the varve measurements in groups of four, as indicated by the broken line near the base of each graph. The Hornbecker and Dunnegan pits appear in a 60-foot terrace bank; the other pits have been dug into the floodplain of the Hudson River.

In figure 2 appears an example of the correlation which Reeds has made of the varves occurring in five separate clay pits at Haverstraw, New York. Seventy varves, with field numbers +20 to +90, serial numbers 231-301, appear on this diagram. The thickness of the "summer" and "winter" layers in each varve has been differentiated, the "winter" band being represented by a black shading, the "summer" layer by the ruled vertical line extending from the base-line upward to the beginning of the winter layer in each section. Five such graphs, one for each pit, appear on the diagram. As the curves closely simulate one another in their oscillations, the correlation may be said to be firmly established. The thickness of the varves in each graph has been averaged and the mean for each determined, as follows: Hornbecker pit, 14.8 millimeter; Dunnegan pit, 15.1 millimeter; Washburn-Fowler pit, 23.9 millimeter; Morrisey pit, 26.0 millimeter; Renn and Archer pits, 27.4 millimeter. This variation in the thickness of the deposits is attributed primarily to their location and elevation, during the deposition of the clay. The Hornbecker and Dunnegan pits, which are a quarter of a mile apart in west Haverstraw, have been cut into the 60-foot escarpment, which is one-half mile distant from the Hudson River. The Washburn-Fowler pit, a quarter of a mile long, stretches lengthwise from near the floor of the Dunnegan pit eastward on the floodplain of the Hudson River. The Morrisey and Renn-Archer pits are deep ones, appearing south of Jones Point, near the Hudson River front, in Haverstraw. They are fully a mile southeast of the Hornbecker, Dunnegan, and Washburn-Fowler pits, in West Haverstraw. The Haverstraw deposits, when contrasted with those in West Haverstraw, show not only a greater average thickness, but particularly so for the corresponding winter layers. These variations are due, no doubt, to a greater depth of water and volume of sediments over the Jones Point area in Haverstraw, although farther from the ice-front, than the terrace banks in West Haverstraw, which were farthest removed from the main channel of the glacio-fluvial river, the Hudson. With a greater depth of water and a larger volume of sediments in the main channel than near the margins of the lake, it is not surprising that during the winter months more clay particles settled down through the cold milky waters to form the thicker "winter" layer at Jones Point than that on the sites of the Hornbecker and Dunnegan pits. Each of the five curves has been smoothed by taking the average of each four successive varves. The smoothed curves have been entered as single-line graphs above the other curves by using the mean of each section as a base line. A comparison of these smoothed curves shows a close agreement in all of the pits. These smoothed graphs represent a sug-

Thickness of winter layers indicated by black shading. The smoothed curve appearing above each of the five graphs is a varve measurements in groups of four, as indicated by the broken line near the base of each graph. The Hornbecker and Dunnegan pits appear in a 60-foot terrace bank; the other pits have been dug into the floodplain of the Hudson River.

gested correlation with the more prominent short-cycle variations of weather and solar radiation as noted by Clayton (1923).

To form a "normal curve" for the entire series of varved clays at Haverstraw, the five partial sections shown on figure 2 and those from other similar sheets were averaged and drawn as one curve to form the Reeds graph represented in the lower portion of figures 3 to 13. The Reeds curve is characterized by dark shading for the winter layers. The Antevs Haverstraw curve, consisting of 732 varves, occupies the middle position, while the curve of the New Haven sediments, representing 343 varves, is placed at the top. The varves as represented in the three curves correlate closely. Each of these curves represents the mean of the varve measurements taken in different clay pits. They are thus "normal curves." Antevs' curves have been developed from measurements taken in the field usually from three to five sections, while the data for Reeds' curve have been taken from field samples preserved in metal trays. The normal number of parallel sections used by Reeds was five, but in some portions of his curve as many as fourteen sections were averaged.

When the Haverstraw and New Haven varved clay graphs are compared they agree closely in contour. The mean, however, of the Reeds Haverstraw curve shows an average thickness of 35 millimeters, the Antevs Haverstraw curve 32.31 millimeters, and the Antevs New Haven curve 23.24 millimeters. These graphs show, furthermore, a variation in the thickness of sediments in groups of three, four, or five years, with occasional larger and smaller groups. This group arrangement suggests a correlation with the weather and solar radiation changes as noted by Clayton (1923). Accordingly, the mean of each four consecutive varves, in each curve, has been taken and set above the normal curve by using the mean of each curve as a base line—that is, the 35 millimeter line in the Reeds curve. The consecutive groups of four varves, which were averaged in this manner, have been joined by a horizontal line near the base of each graph. The Reeds Haverstraw curve has been further smoothed by taking the mean of each two consecutive groups of four varves—that is, eight varves, as indicated on the charts; also of every eleven varves. According to Clayton, the eight- or eleven-year curves give some idea as to what the sun-spot curve for this 736-year period might have been like.

These smoothed curves show not only the more prominent group fluctuations in the deposition of the clay, but also those minor stages in the melting of the retreating icefields. When the curve is above the mean, it indicates a period of more active melting and deposition and the reverse conditions when it is below.

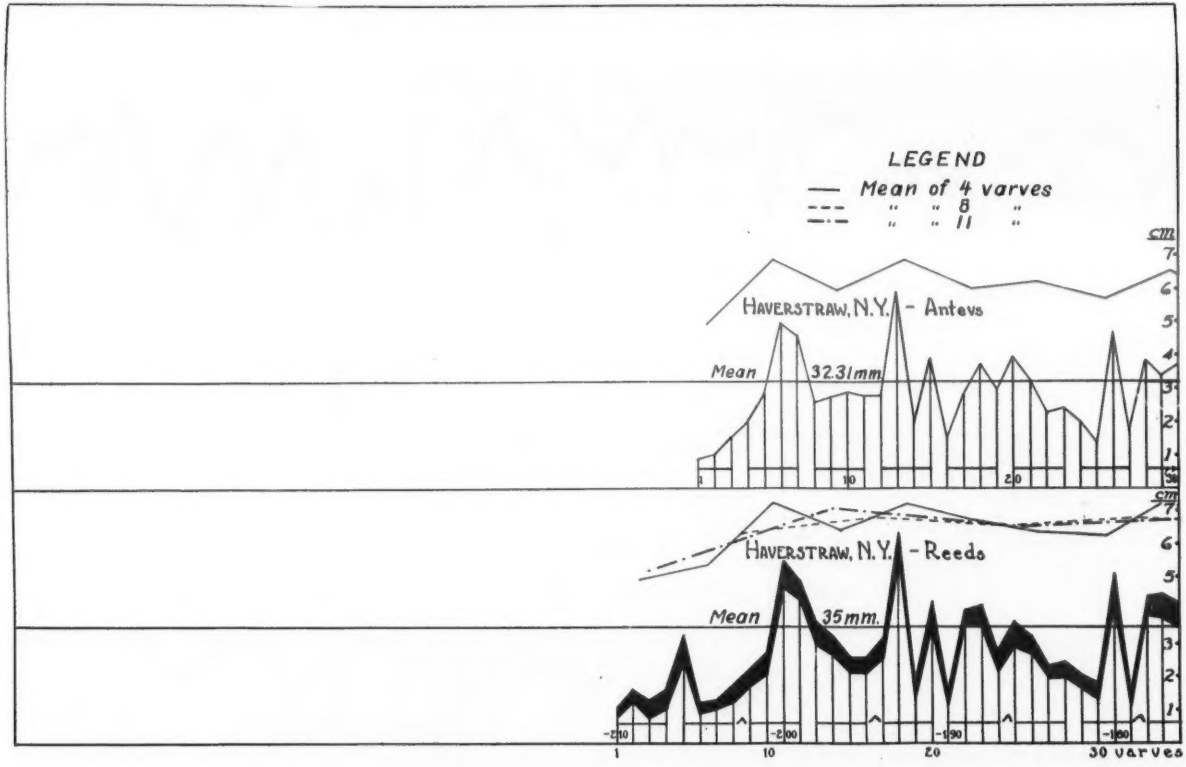

FIGURE 3.—*"Normal Curves" of the lowest Varves in the Haverstraw, New York, Clays*
As determined by C. A. Reeds and E. Antevs, working independently. Base not reached. Thickness of winter layer represented by dark shading in Reeds' curve. Smoothed curves by Reeds have been placed above each graph.

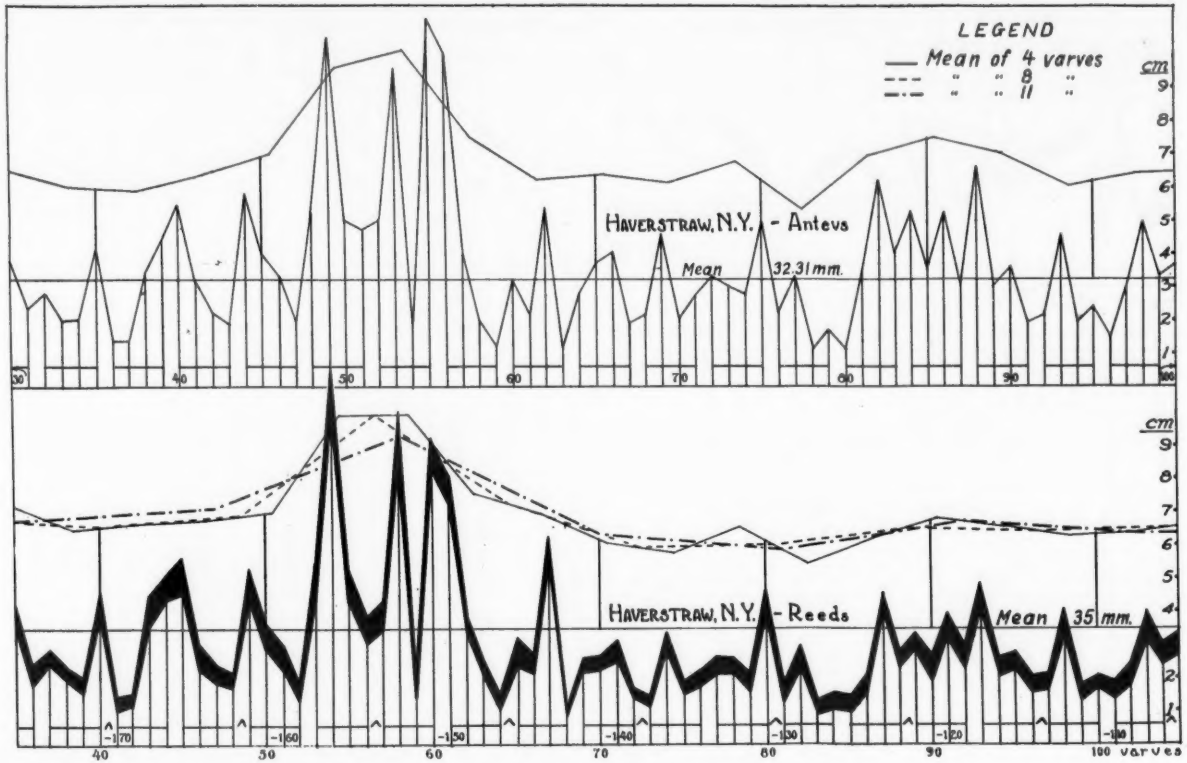

FIGURE 4.—*Normal Curves of Varves 35-105 at Haverstraw, New York*
As determined by C. A. Reeds and E. Antevs, working independently. Smoothed curves and means by Reeds in this and the following diagrams.

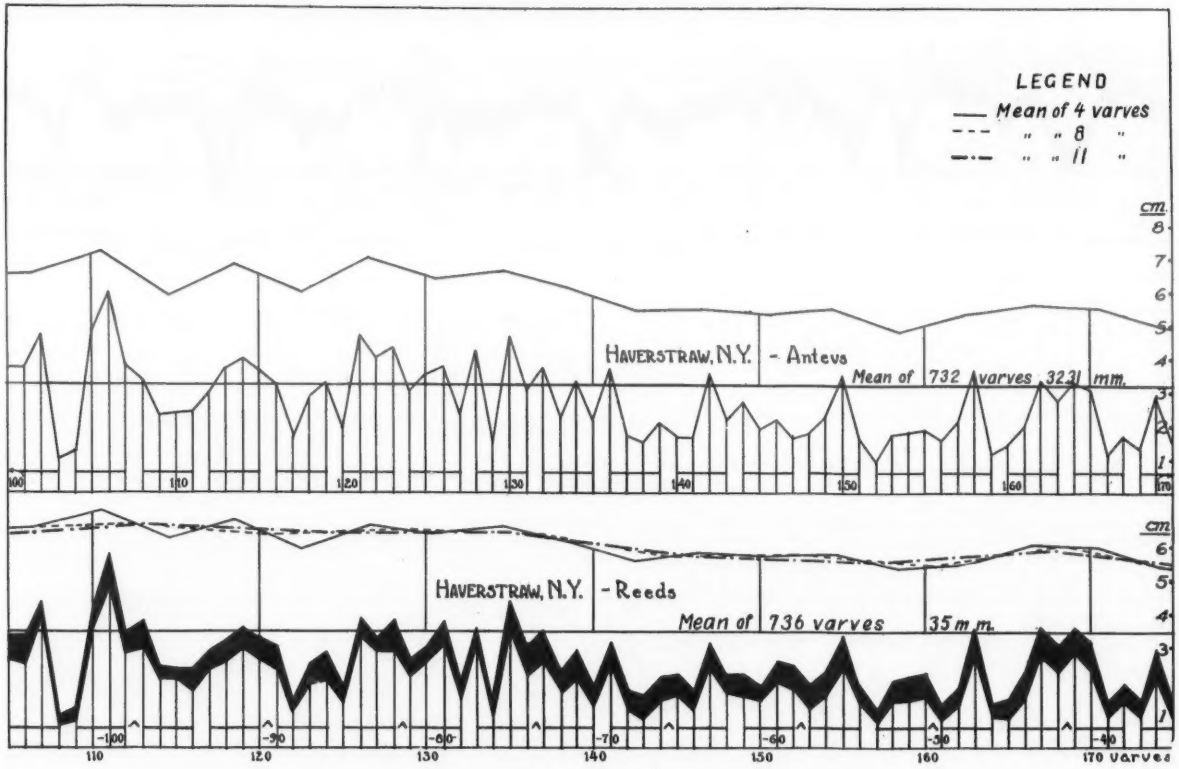

FIGURE 5.—*Normal Curves of Varves 95-175 at Haverstraw, New York*
As determined by C. A. Reeds and E. Antevs.

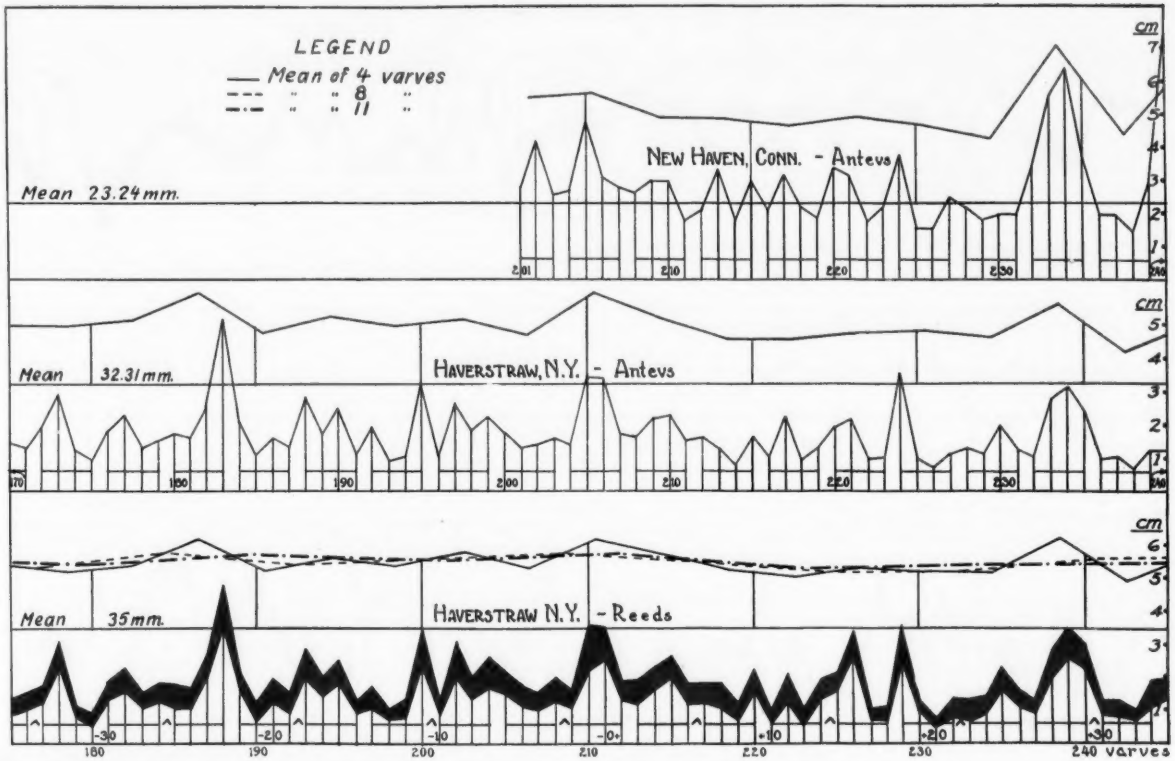

FIGURE 6.—*Normal Curves of Varves 175-245 at Haverstraw, New York, and New Haven, Connecticut*
As determined by C. A. Reeds and E. Antevs.

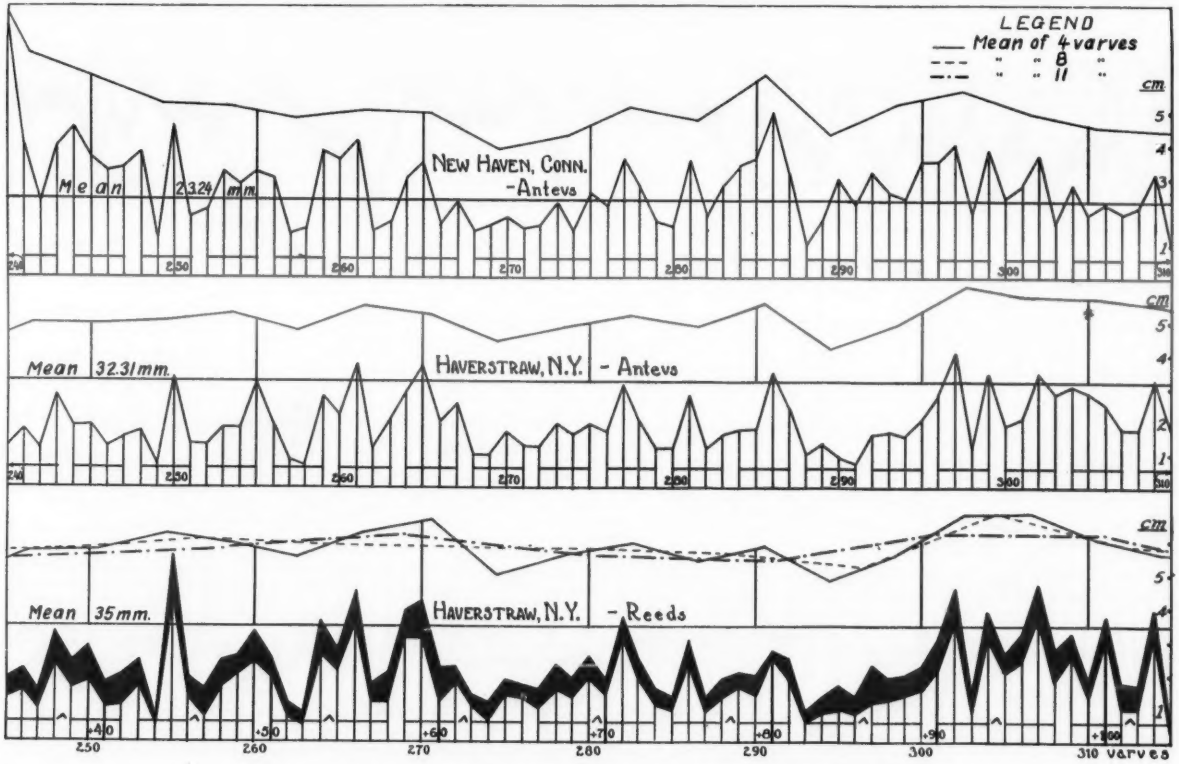

FIGURE 7.—*Normal Curves of Varves 245-315 at Haverstraw, New York, and New Haven, Connecticut*
As determined by C. A. Reeds and E. Antevs.

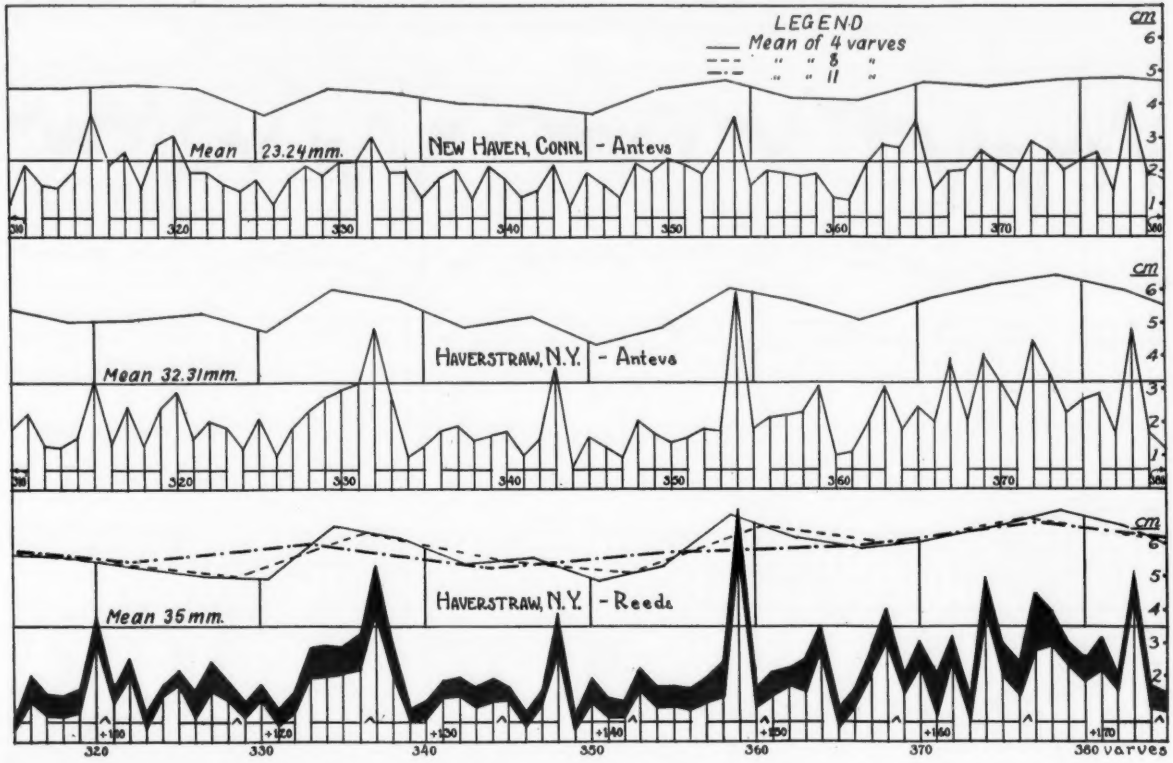

FIGURE 8.—*Normal Curves of Varves 315-385 at Haverstraw, New York, and New Haven, Connecticut*
As determined by C. A. Reeds and E. Antevs.

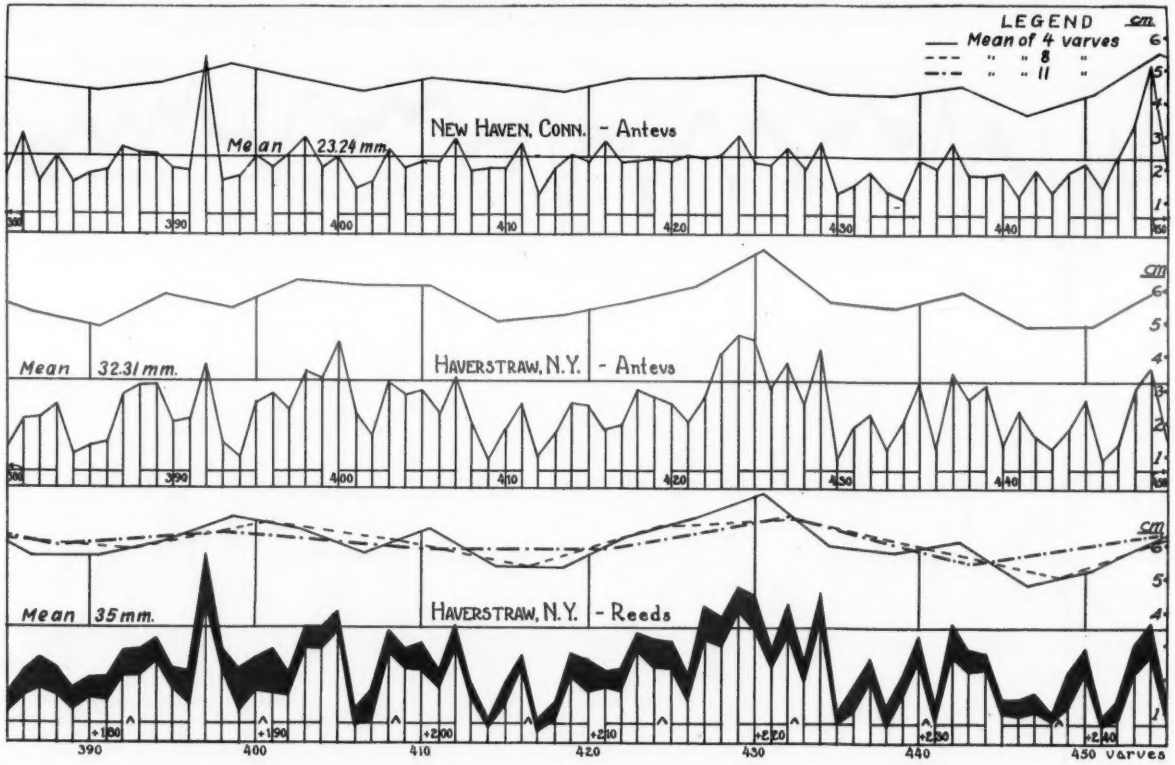

FIGURE 9.—*Normal Curves of Varves 385-455 at Haverstraw, New York, and New Haven, Connecticut*
As determined by C. A. Reeds and E. Antevs.

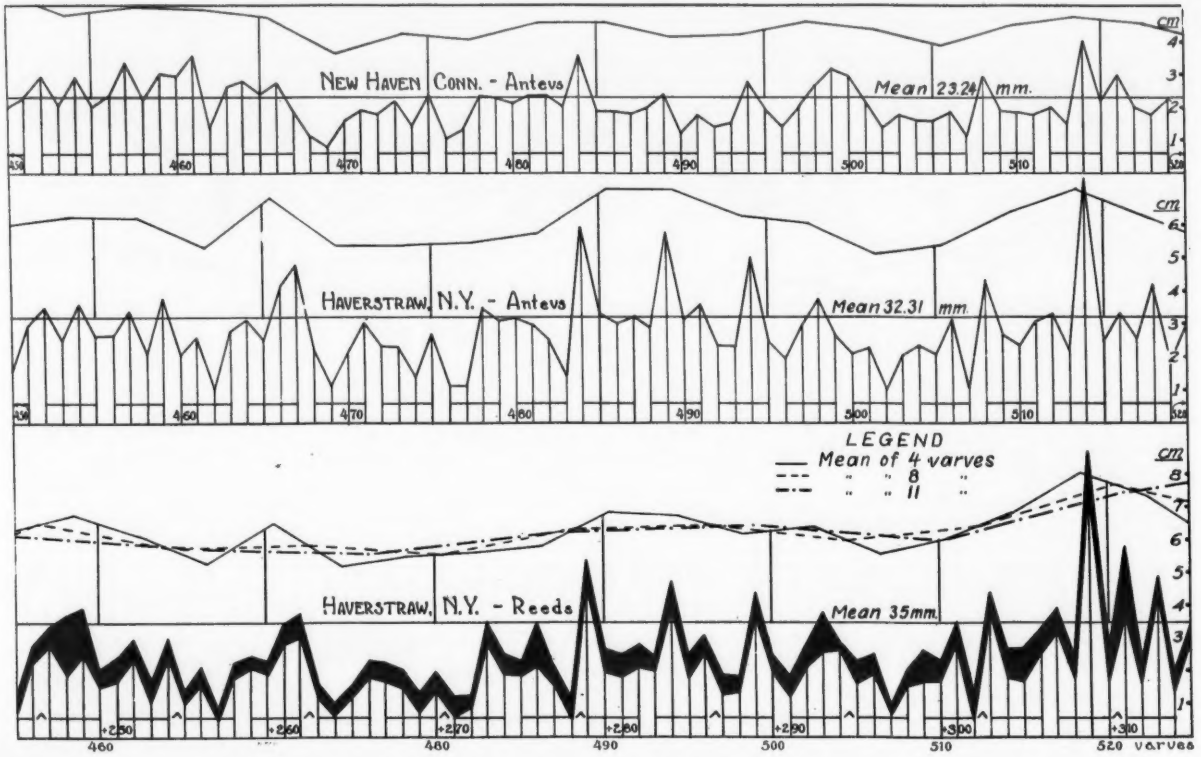

FIGURE 10.—*Normal Curves of Varves 455-525 at Haverstraw, New York, and New Haven, Connecticut*
As determined by C. A. Reeds and E. Anteva.

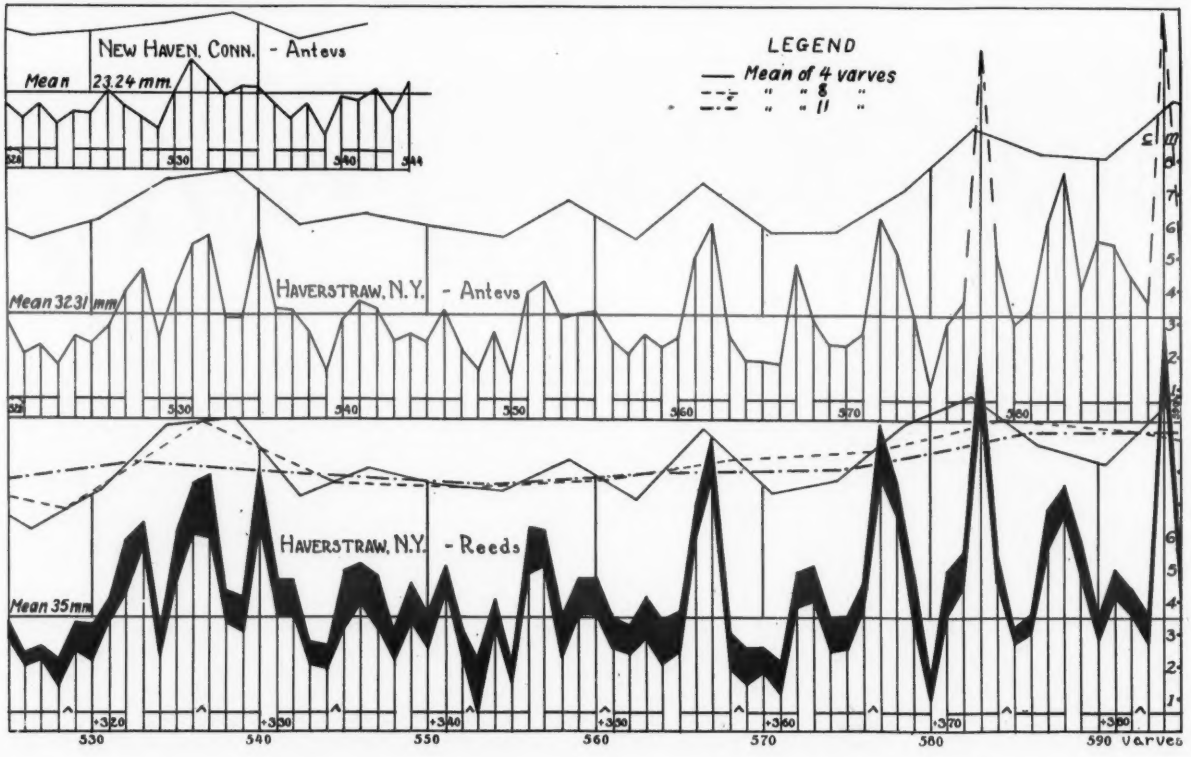

FIGURE 11.—*Normal Curves of Varves 525-595 at Haverstraw, New York, and New Haven, Connecticut*
As determined by C. A. Reeds and E. Antevs.

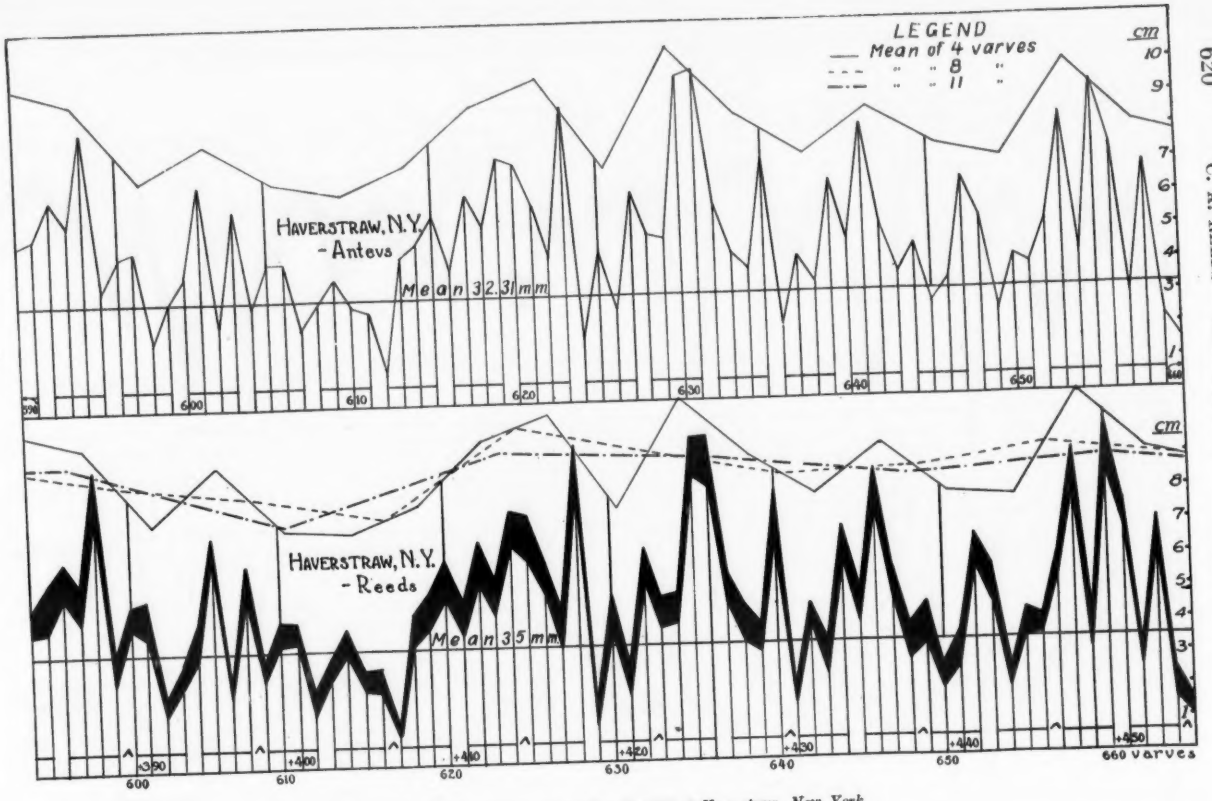

FIGURE 12.—*Normal Curves of Varves 595-665 at Haverstraw, New York*
As determined by C. A. Reeds and E. Antevs.

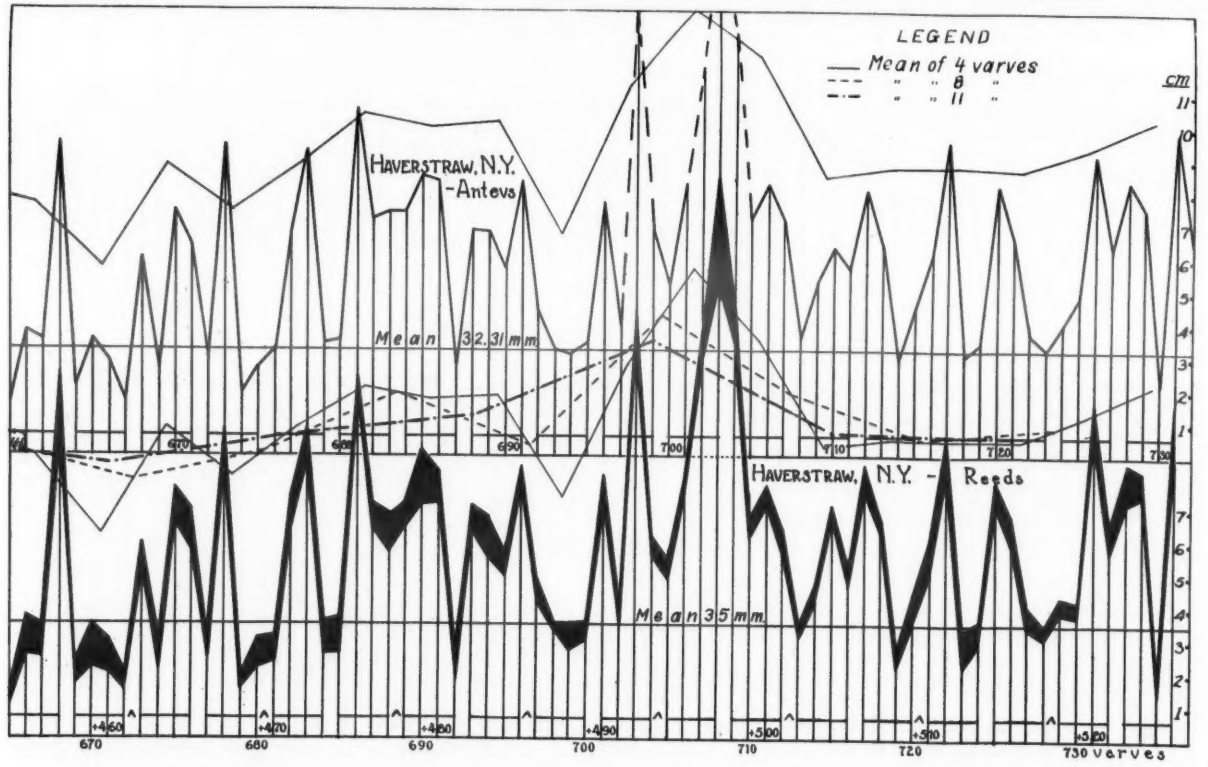

FIGURE 13.—*Normal Curves of Varves 665-737 at Haverstraw, New York*
As determined by C. A. Reeds and E. Antevs.

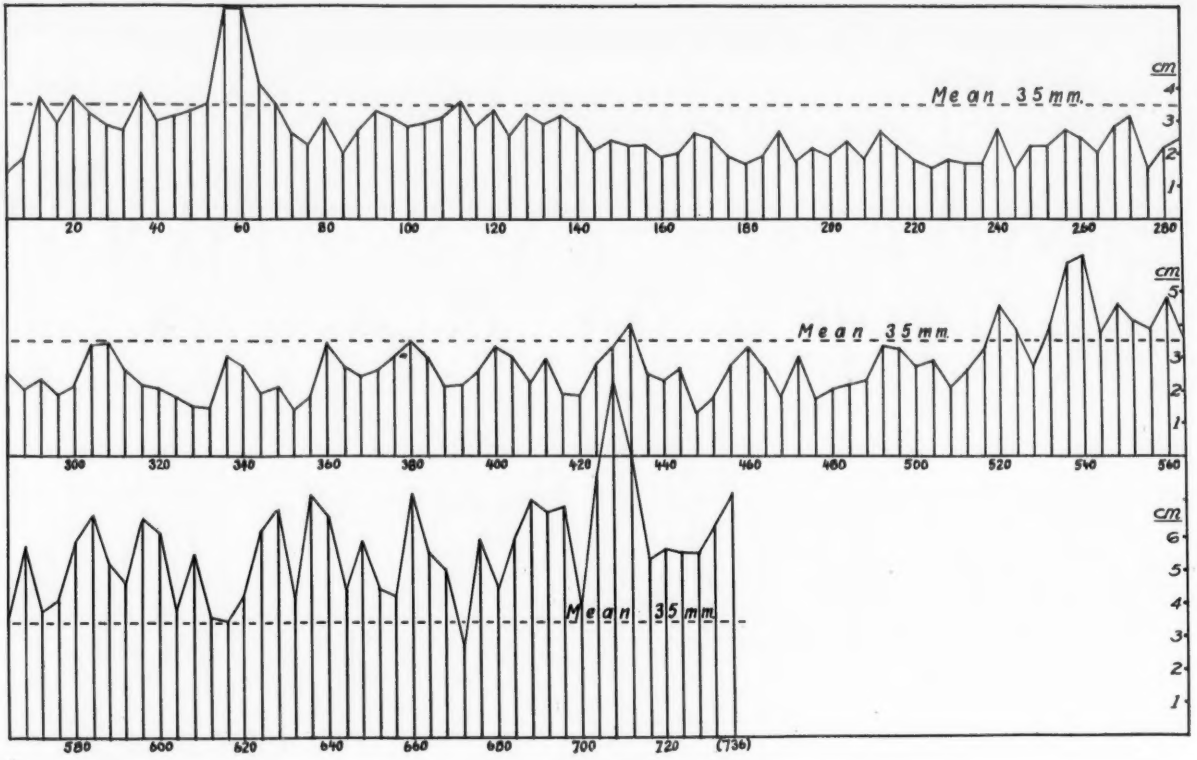

FIGURE 14.—*Diagram of a smoothed Curve*

This smoothed curve represents the mean of each successive group of four varves at Haverstraw, New York, as entered on vertical spacings one-half of a centimeter apart. The mean for the entire series of 736 varves is 35 millimeters. Original drawing reduced one-half.

In figure 14 the smoothed curve, derived from Reeds' normal curve by taking the mean of each successive group of four varves, has been arranged on the graph spacing used in figures 2 to 13. This arrangement permits the entire smoothed curve of 736 varves to be placed on one sheet. The annual varves do not appear. It also affords an opportunity to see at a glance the more prominent major fluctuations and periodicities in the melting of the ice. Regular cycles are not apparent. The first prominent warm period was for the years 52-68. This was followed by a comparative cold period to the 112th year, but it was not as cold as during the next 192 years, terminating with varve 300. For eight years, 300-308, the melting of the ice almost reached the normal between cold and warm temperatures. From 308 to 332 the curve moves gradually downward, indicating a 24-year period when the successive summers were progressive colder. Then, during the next 204 years, there follows a series of short cycles of warm and cold periods of varying length, which were for the most part below normal, terminating with 528 years. Then, curiously enough, the last 208 years, 528 to 736, were cyclic in form, but predominantly warm—that is, above the normal or mean line. When an opportunity has arisen to check varves 52 to 68 and 700 to 716 with varves from other localities, then we shall know whether these abnormal fluctuations were caused by excessively warm periods or were accentuated by local causes.

Periodicities in Varve Clay Graphs and Tele-Connections

Periodicities in varve graphs have been noted by W. Köppen (1928), C. E. P. Brooks (1928), and E. Antevs (1929). Köppen recognized periods of 2, 3, 4, 5, 6, 7, and 8 years in North American varves, with the period of 2, 3, 4, and 5 years being frequent. Brooks has analyzed the tele-connections of De Geer between Sweden, North America, Argentina, and India. In Argentina he notes cycles of 5.1, 10.4, and 51 years in a curve secured by Dr. Caldenius at Lago Corintos, which was described and figured by De Geer (1927). The period of 10.4 years noted by Brooks approaches the 11-year sun-spot curve in length, but not in rhythm. In fact, Brooks comments on the almost entire absence of an 11-year periodicity in the varved clays. Antevs states that while stadial moraines indicate the periodical retreat of the ice-edge and are especially suited for long-range periodic phenomena, the clays enable us to determine the exact length and character of the periods. The varve graphs are best suited for the study of short cycles. He regards the almost complete absence of the 11-year cycle in the curves studied by Brooks as being perhaps the most important result so far obtained from the analyses of varve curves.

Brooks (1928), in discussing De Geer's (1926) tele-connections between Zealand (Denmark) and the Little Ferry, New Jersey, clays of the Hackensack Valley, which were described and diagramed by Reeds (1926), calls attention to two correlation coefficients, one of +.35, which suggests that the tele-connections appear to be undeniable; the other of +24, which shows that nearly half the apparent connections are due to a two-year periodicity common to both. Brooks makes further comments, but it does not seem desirable to feature them, since De Geer's correlations in this instance are premature and misleading. Reeds informed De Geer of this fact in August, 1927.

On plate II (1) De Geer attempts to correlate (1) the Swedish curve, years 5540 to 5629, with portions of Reeds' Hackensack curve and Antevs' Connecticut Valley curve; (2) through years 5629 to 5684 he arranges the Hackensack and Connecticut Valley curves in juxtaposition; (3) for years 5666 to 5892 he places Hackensack varves opposite Scanian (southern Swedish) varves; (4) for years 5736 to 5869 he diagrams varves from Dutchess Junction, New York, opposite those from Hackensack and Scania.

The objections to the aforementioned tele-connections are as follows:

A. The agreement between the various graphs is apparently not close enough to suggest a correlation.

B. The direction of ice-retreat from the terminal moraine on Staten Island and Long Island was northward up the Hackensack, Hudson, Connecticut, and smaller river valleys. As the ice-border, which extended in a general east-west direction, retreated northward at a rate somewhat less than 100 feet per year, clays were deposited in marginal glacial lakes in the separate river basins. The Hackensack Valley clays at Little Ferry, New Jersey, are the southernmost exposures and consequently the oldest known in eastern North America. Twenty-five miles to the north of Little Ferry, and in direct line of retreat of the ice, is Haverstraw, New York, with the oldest clays appearing in the Hudson River basin. The Hackensack and Hudson River basins, although parallel for nearly fifty miles, are separated by the Palisade Ridge and Verdriderger Hook. Fifteen miles to the north of Haverstraw, in direct line of retreat of the ice and on the north side of the Highlands of the Hudson, is Dutchess Junction, New York.

C. Antevs (1928) has definitely correlated the Haverstraw clays with those in the Quinnipiac River basin at New Haven, Connecticut. Likewise he correlates the Dutchess Junction clays with Hartford, Connecticut, clays. The 2,500 varves in the Hackensack clays, being older than the Haverstraw clays, are not considered in the correlations

which Antevs has established between Connecticut localities and the Hudson River Valley.

D. The geographical position of the localities in New Jersey, New York, and Connecticut with reference to ice-retreat and deposition, as well as the correlations which Antevs has established in eastern North America, render De Geer's correlation of Hackensack clays with Dutchess Junction and Connecticut Valley clays as premature and misleading. It will be necessary for Brooks to revise his coefficients of correlation again when the tele-connections between Sweden and eastern North America have been established.

Suggested Correlation of Solar Radiation, Weather, and Varved Clay Variations

It has been stated that the character of the weather during the melting period of the ice varied from year to year, and that these fluctuations are reflected in the varying thickness of the annual deposits (Bruckner, 1921; Osborn and Reeds, 1922; Sauramo, 1929). After calling attention to wide range correlations or tele-connections between Sweden, North America, Argentina, and northwestern Himalayas, in which more than 80 per cent of the varves are said to agree, De Geer (1927) states:

> "This remarkable coincidence of such rapid variations at such considerable distances, caused by simultaneous ice-melting, seems not to be explicable in any other way than by variations in the amount of heat from the sun."

De Geer (1926) states that the rate of melting depends almost entirely on the intensity of solar radiation. In those temperate regions which were glaciated during the Pleistocene epoch he considers that practically all of the solar radiation was spent in melting the accumulated snow and ice, while now, after the yearly snow and ice is melted, the balance is available for warming the ground. During the retreat of the ice he notes that the changes in solar radiation correspond fairly well with the changing amount of melting water. Since this water found its way to the ice-edge, he considers that the amount of reassorted morainic material eroded and carried away by the subglacial rivers varied very nearly at the same rate as the amount of melting water. Furthermore, by getting accurate measurements of the annual amount of the finest and most regularly deposited sediment from such waters (varved clays), he considers it would be about the same as getting readings from a gigantic natural self-registering thermograph. Brooks (1928) suggests solarigraph for thermograph.

A comparison of figure 1 with figures 2 to 13 shows that the solar radiation variations, when plotted in the same manner, are not different

in kind from those of the varved clays. In fact, it is surprising how close the solar fluctuations simulate those of the varved clays. No direct comparison can be made between them, since the years represented in figure 1 and 2 to 13 are not contemporaneous. The close agreement in the form of the graphs, however, leads one to offer a tentative correlation of the annual solar radiation variations with those of the varved clays. Clayton has shown that there is a real relation between solar radiation variations and weather changes; and, since weather affects the conditioning of glaciers and is reflected in the varve graphs shown herewith, a suggested correlation of solar radiation weather and varved clay variations is here proposed.

Conclusion

It may be stated that weather, as distinguished from climate, affects the conditions of ice-masses daily, seasonally, annually, and in groups of years of varying length. Glaciers are conditioned by opposing factors, nourishment and depletion. These, in turn, are governed by changes in the weather and in the amount of solar heat. The intensity of solar radiation reaching the earth is affected by the amount of water vapor, carbon dioxide, ozone, and dust in the air; also by irregular variations in the sun itself. The variations in the sun fluctuate slightly about a mean of 1.938 calories per minute per square centimeter. Although these solar variations are moderate, they are important, for a real relation between them and weather changes, as well as glacial conditions on the earth, is strongly suggested. The records preserved in living and fossil trees and varved glacial clays show not only seasonal and annual variations, but also fluctuations for irregular groups of years, which seem difficult to explain on any other grounds than a real relation between them and the changes in weather and solar radiation.

The graphs of solar constant and varved clay variations appearing in this paper show that they are not unlike; in fact, they bear close resemblances. Short cycles, averaging four years in length, are prominent, as shown by the smoothed curves. Longer periods, as noted in figure 14, are not wanting.

A special study of Haverstraw and New Haven varved clays shows that their fluctuations are not due to local causes, but to primary factors embracing a strict periodicity in the melting of the ice, summer by summer. The fact that these fluctuations vary from year to year, and for short as well as for long irregular cycles, shows that these variations were governed by changes in the weather and solar radiation extending over a period of more than seven and one-third centuries.

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MAPS OF THE PLEISTOCENE GLACIATIONS

BY ERNST ANTEVS

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Prefatory Note by the Glacial Committee

The "Maps of the Pleistocene glaciations" and the accompanying report by Dr. Ernst Antevs were presented in preliminary form before a joint session of the American Association for the Advancement of Science and the Geological Society of America, held in New York on December 27, 1928. The occasion was a symposium on "The centenary of the glacial theory," which constituted a part of the program of the annual meeting of these and affiliated societies.

As early as April, 1928, Prof. Henry Fairfield Osborn, President of the American Museum of Natural History and of the American Associa-

tion for the Advancement of Science for 1928, requested that special maps of the Pleistocene glaciations of the Northern Hemisphere be prepared for presentation at the meetings held during Christmas week. To facilitate the preparation of these maps he appointed a committee consisting of Prof. Frank Leverett of the United States Geological Survey, Prof. Charles P. Berkey of Columbia University, Dr. Isaiah Bowman of the American Geographical Society, and Dr. Chester A. Reeds of the American Museum. As no one member of the committee, nor the committee as a whole, had sufficient time to assemble the available data, which were widely scattered in numerous scientific papers and published in several languages, the committee recommended that Dr. Antevs be engaged to assemble the data, compile the maps, and write a report concerning them.

At the request of President Osborn and members of the committee, the Carnegie Institution of Washington granted a sum sufficient to pay the cost of preparing the maps. This sum included Dr. Antevs' salary for eight months, the cost of making photostats of existing glacial maps, the salaries of Messrs. George Pinkley and Erwin J. Raisz, draftsmen, and incidental expenses. The cost of publishing this paper has been borne by the Geological Society of America.

The initial plan was to present detailed maps showing the Pleistocene glaciations of the Northern Hemisphere only. After the preliminary display of these maps in December, 1928, Dr. Reeds, of the committee, suggested that maps showing the glaciated areas in the Southern Hemisphere, as well as those of the Northern Hemisphere be prepared, and that the cost of publication might be greatly reduced by the use of sketch maps. Such an arrangement would not only greatly facilitate the publication of the data on a larger scale, but enhance its value for teaching purposes and at the same time reduce the cost of publication. Twenty-one sketch maps have thus been prepared for this report.

In this research Dr. Antevs was greatly aided by the library facilities of the following institutions: The American Museum of Natural History, the American Geographical Society, and Columbia University. The work was conducted primarily in the Geological Department of the American Museum of Natural History, where a special room was set aside for the investigation. The photostating of existing glacial maps was done in the laboratory of the American Geographical Society, New York.

The committee is grateful to all the individuals, societies, libraries, and corporations that have aided in this work. Its special thanks are due to Dr. Antevs for having undertaken and performed in a highly

creditable manner a very difficult task. The committee hopes that the results of this survey may lead to a better understanding of existing glacial deposits and a more thorough investigation of Pleistocene glacial action in all lands.

FRANK LEVERETT.
CHARLES P. BERKEY.
ISAIAH BOWMAN.
CHESTER A. REEDS.

INTRODUCTION

The effect of the Pleistocene glaciations on the migrations and distribution of plants and animals, including man; on the position of the seashore, and on other significant features makes it highly desirable to know accurately the positions and the extent of the Pleistocene icesheets and glaciers. The material available to show the number and extent of the Pleistocene glaciations is heterogeneous, and the views held in different countries and by different geologists are diverse, so that the compilation of this report has been difficult. The known data have been compiled and combined in what is believed to be a reasonable way and few generalizations have been made.

I am greatly indebted to President Henry Fairfield Osborn, President John C. Merriam of the Carnegie Institution, and the Glacial Committee for the opportunity to compile the maps. I am also grateful to Prof. Frank Leverett for generously supplying outlines of the drift borders from New York City to the Dakotas; to Dr. Chester A. Reeds, secretary of the committee, for much good advice and help; to Dr. W. C. Alden for valuable data; to Dr. Paul Woldstedt for supplying drift borders in Germany and Poland; to Mr. O. M. Miller for advice and suggestions regarding the base maps; and to Messrs. George Pinkley and Erwin J. Raisz for assistance in drafting the maps.

EXISTING GENERAL MAPS OF THE PLEISTOCENE GLACIATIONS

The existing maps of the Pleistocene glaciations may be divided into world maps, hemispherical maps, continental maps, and regional maps. The regional maps, which are very numerous, will be considered in another part of this report.

The world maps are designed to show at a glance the relations of the Pleistocene glaciers to the oceans and to the earth's surface, but they are too small to show details. With two exceptions, those maps are prepared on the Mercator projection, by which the whole globe may be shown on a small scale and latitudes are comparable. The areas shown are not comparable, however; and, as the glaciers were formed in middle

and high latitudes, this projection gives the ice-covered areas an undue prominence. The first Mercator map of the Pleistocene glaciation may have been that of Supan, published in 1885. Later editions were published, the sixth in 1916. Other similar maps were given by Hess in 1904, by Arldt in 1907 (plate 22), by the Encyclopædia Britannica in 1910 (Vol. 12, page 57), and by Schuchert in 1914 (page 266[1]).

A correct idea of the extent of the glaciated areas may be had from Levy's map in Mollweide's equal-area projection, published in 1915, and from Machatschek's map in Aithoff's equal-area projection, published in 1927. Maps of this type have to be made very large in order to give proper conceptions, and their peripheral parts are greatly distorted.

In order to show the positions of the glaciated areas in relation to the poles and the oceans, polar hemispherical maps have been prepared. The first maps of this kind, prepared by Penck, were published in 1882. These maps appear to represent the first attempt to show the entire Pleistocene glaciation. I have not seen these maps, but Berghaus's maps, drawn in 1884 and published in 1892, are revisions of them, according to Levy (1915, page 36). These maps show the north and south polar regions on Lambert's equal-area azimuthal projection, and include the Pleistocene as well as the modern glaciations. Penck's northern hemisphere map, further revised, is included in Haug's textbook issued in 1911 (page 1871) and other publications. A different method of showing the glaciation in the Northern Hemisphere was attempted by Walther in 1912 (page 149).

Another type of hemispherical map divides the earth according to the distribution of land and water; so that the Arctic regions, Eurasia, Africa, and the Americas down to latitude 20 degrees south are shown on one map, and the remainder of the earth's surface on another map. The first map of this kind, which was prepared in equal-area azimuthal projection, appeared in Andrees Handatlas, fourth edition, published in 1899. This map appears unchanged in later editions of that atlas, including the eighth, published in 1922. A glacial map of the land hemisphere on the same projection was given by de Martonne in 1909 (page 597) and in 1926 (page 849). All these maps show well not only the position of the ice-sheets but their size in true relation to the earth's area.

Finally the Pleistocene glaciation was shown on maps of the eastern and the western hemispheres by Keilhack in 1920 (page 149) and in 1926 (page 456).

[1] The publications containing these maps and the others here mentioned are shown in the bibliographies given at the end of this report.

FIGURE 1.—*Northern Hemisphere*
Maximum extent of areas glaciated at one time or another during the Pleistocene. Lambert's equal area projection. Scale, 1:100 million.

Maximum extent of areas glaciated at one time or another during the Pleistocene. Lambert's equal area projection. Scale, 1:100 million.

FIGURE 2.—*Northern Hemisphere*

North America and northern Europe: areas glaciated during the last glaciation; Asia and mountains in Europe and America: areas glaciated at one time or another during the Pleistocene. Lambert's equal area projection. Scale, 1:100 million.

Maps showing the extent of the glaciated regions and of the different glaciations in the separate continents have probably been reproduced more frequently than any other kind. Perhaps the earliest map showing the glaciated regions of Europe was compiled by Penck and published in 1887 (page 25). Among other maps showing these regions are those compiled by Neumayr in 1895 (page 430), by De Geer in 1896, and by Penck in 1905. More pretentious are Geikie's maps, published in 1895 (pages 437, 465, 475), which attempt to show the second, third, and fourth glaciations. Revised editions of these maps reappear in Geikie's last comprehensive treatise on the ice-age of Europe, published in 1914. Still other maps, each usually a revision of an earlier one, differentiating two or three ice-sheets, were given by Dana in 1895 (page 976), by De Geer in 1896, and by Sederholm in 1911 (also in Atlas de Finlande, published in 1910, map 5). Maps are given also by Leverett in 1910, and by Osborn and Reeds in 1922 (pages 416, 442). The much-discussed boundaries of the last Fenno-Scandian ice-sheet were sketched by Ussing in 1903 (pages 12, 164), and by Enquist in 1918 (page 82).

The southern boundary of the drift-bearing area, as well as morainic lines in North America from the Atlantic seaboard to Montana, were shown by T. C. Chamberlin in 1883. Maps of North America during the Ice Age were given by G. F. Wright in 1889 (page 163), by T. C. Chamberlin in 1895 (in Geikie, 1895, page 724), and by Dana in 1895. Similar maps showing the extent of land that was covered by ice were given by Chamberlin and Salisbury in 1906 (pages 329, 331), by Osborn in 1910 (page 485), by Leverett in 1910 (plate 1), by Tarr and Martin in 1914 (page 261), and by Alden in 1924 (page 32). The large wall map by T. C. Chamberlin, published in 1913, deserves special mention.

The Pleistocene glaciation and snow-line on the mountains in the western part of the United States is shown on a map prepared by Louis in 1927.

The Quaternary glaciation in South America was well shown by Sievers in 1911 and 1914 (page 64).

The areas in Asia that were glaciated at one time or another during the Pleistocene epoch were shown on small-scale maps by Geikie in 1895 (page 641), by Obruchev in 1926 (plate 10), and by Berkey and Morris in 1927 (page 383).

Ice-Sheets in North America

STAGES DISCRIMINATED

In Iowa the Nebraskan, Kansan, Illinoian, Iowan, and Wisconsin glacial stages have been distinguished. These stages were separated by

the Aftonian, Yarmouth, Sangamon, and Peorian interglacial stages. Not so many separate drift sheets have been distinguished in other States, but more than one has been observed in the peripheral belt of the ice in every State west of New York City. The older drift sheets, of course, have been satisfactorily mapped only where they extend farther out than the younger ones.

The southern boundaries of the Pleistocene ice-sheets in the States from New Jersey westward to the Dakotas have been compiled almost entirely by Professor Leverett. Much valuable information regarding the drift borders in the Western States has been supplied by Dr. Alden.

The quality of the glacial data varies greatly. By the indefatigable work of American geologists the drift borders from the Atlantic coast westward to Montana have been mapped in great detail and are better known than those in any other part of the world. In the Northwestern States they are not so well known, and the maps of them made by different geologists differ considerably.

NEW ENGLAND

The Pleistocene ice-sheets probably extended out into the Gulf of Maine, where their extent and outline may have been determined by calving, which in turn was dependent chiefly on the depth of the water. They may have had a reentrant corresponding to the deep central parts of the gulf. The last ice-sheet reached the east coasts of Nova Scotia and Nantucket.

In southern New England and Long Island one or more drift sheets are recorded beneath the Wisconsin deposits, which here form the outer limit of the glaciated area. The Wisconsin drift border, which is mapped in great detail, runs through Nantucket, Marthas Vineyard, Block Island, and southern and central Long Island to the mouth of the Hudson. (Woodworth, 1897; Fuller, 1914; Goldthwait, 1922).

NEW JERSEY

In New Jersey, where the Wisconsin border has been well mapped (Salisbury and others, 1902, plate 8), an old Jerseyan drift has long been distinguished (Lewis and Kümmel, 1915, page 73), and a revision of the outermost glacial deposits has just been made by Professor Leverett (1928, and personal communication). By this work not only the extreme borders of the Wisconsin and the Jerseyan drifts were definitely located, but also Illinoian drift was distinguished by means of the degree of weathering and the decay of the material. Illinoian drift occurs in a lobate belt outside of the Wisconsin border from Summit westward into Pennsylvania. Jerseyan drift, which according to Leverett is to be correlated with either the Kansan or the Nebraskan of the Middle

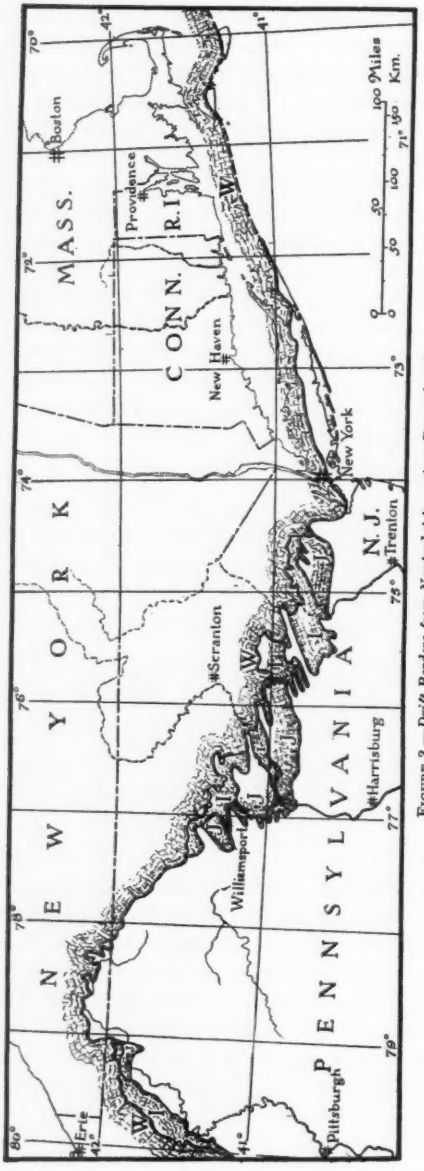

FIGURE 3.—*Drift Borders from Nantucket to western Pennsylvania*
J, I, W designate the Jerseyan, Illinoian, and Wisconsin glaciations. Scale, 1 : 5 mi l on.

West, covers a large area west of Morristown and Somerville, as well as four small areas inside the Illinoian drift border, near the Pennsylvania State line.

PENNSYLVANIA

The northeastern and the northwestern parts of Pennsylvania were invaded by Pleistocene ice-sheets. While one ice-lobe pushed down over New England, New York, New Jersey, and Pennsylvania, another lobe expanded over the region south and southwest of the Great Lakes. South of the western part of Lake Ontario there was a deep and broad reentrant extending into New York State.

The drift borders in Pennsylvania have been revised during the last few years (Ashley, 1927; Leverett, 1928), and Leverett has supplied the material for the present maps. The Wisconsin ice-border of Lewis and G. F. Wright (Lewis, 1884; Wright, 1890) was largely retraced and was corrected for details. A considerable part of the pre-Wisconsin drift of

eastern Pennsylvania and the main part of the pre-Wisconsin drift of northwestern Pennsylvania are now regarded as of Illinoian age. The Illinoian ice seems to have sent out long lobes in the valleys of the northeastern part of the State.

About one-half of the old drift beyond the Wisconsin boundary may be Jerseyan, which Leverett thinks is a correlative of the Kansan or the Nebraskan of the Middle West. This old drift lies, of course, mainly outside that of the Illinoian drift, in which, however, it occurs in a few small patches.

Beside these surely established drifts, the Wisconsin, Illinoian, and Jerseyan, there is, according to Leverett, a fourth still older drift, which, however, is not indicated on the present maps. This questionable drift covers a large area east of the 76th meridian between latitude 40° 30′ and 40° 45′. It also covers another large though narrow region outside the established borders of glaciation from a point in latitude 40° 45′ north, longitude 77° west, to a point in latitude 41° 45′ north, longitude 77° 40′ west. It likewise covers a small tract in latitude 41° 45′ north, longitude 79½° west.

OHIO

In Ohio the Illinoian and the Wisconsin glaciations have been extensive. The Wisconsin ice-sheet reached beyond the limit of the Illinoian sheet in the eastern part of the State and nearly down to it in the western part. Both drift borders trend from northeast to southwest, forming the eastern margin of the Great Lakes ice-lobe. The Illinoian border was revised by Leverett in 1924 and 1925 and the Wisconsin border in 1925. Many details were then improved, as may be seen by a comparison with Leverett's earlier map (1915, plate 5, page 62).

KENTUCKY

One ice-sheet, the Illinoian, surely reached Kentucky, and another probably did. The Illinoian ice encroached over a narrow zone in the northwestern part of the State at and southwest of Cincinnati. Its border was revised and slightly changed by Leverett in 1924 (cf. Leverett, 1915, page 62).

In northeastern Kentucky, in the region north of latitude 38 degrees north and east of longitude 85 degrees, there are pebbles and boulders derived from the Ottawa-Quebec region, in southern Canada (Jillson, 1925; 1927, pages 123-141). They may have been brought either by an ice-sheet or by floating ice in an ice-dammed lake, probably during Nebraskan age.

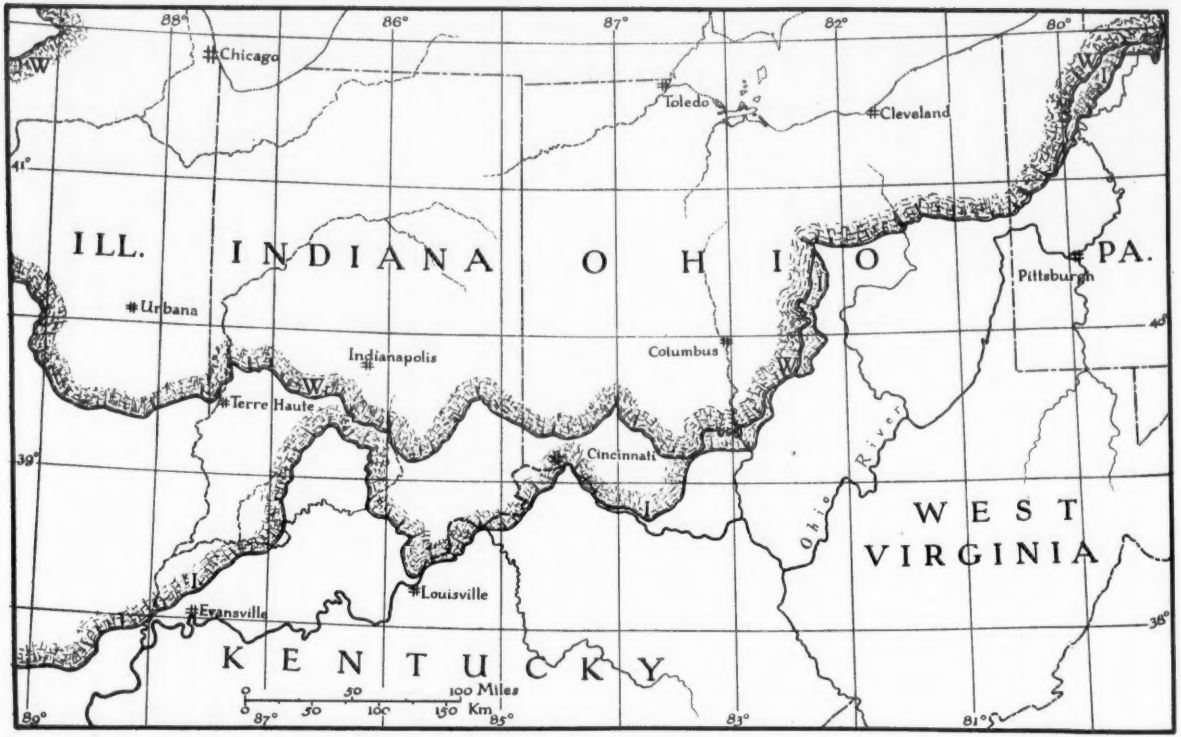

FIGURE 4.—*Drift Borders from western Pennsylvania to central Illinois*
I and W designate Illinoian and Wisconsin glaciations. Scale, 1 : 5 million.

INDIANA

In Indiana, as in Ohio, the Illinoian and Wisconsin drift sheets form the surface deposits. Leverett revised the Illinoian border in 1924 and made slight changes in details from his previous mapping (Leverett, 1915, page 63, plate 32). The Wisconsin border on our maps is copied from Leverett. The Wisconsin ice-sheet reached in this State slightly farther south than in Ohio and Illinois, attaining its most southerly point at 39° 5′ north.

ILLINOIS

In Illinois three different drifts may occur at the surface. The lobes attained their greatest development in this State, where at least two ice-sheets reached their most southerly points. The lobes have a rather smooth outline, there being practically no marked protruding parts.

Pre-Illinoian drift, correlated with the Jerseyan in New Jersey and Pennsylvania, and of either Kansan or Nebraskan age, occurs on the Mississippi in the southwestern part of Illinois (Leverett, 1924, and personal letter). Illinoian drift extends nearly to the southern and western boundaries and beyond them at Saint Louis and in southeastern Iowa (Leverett, 1899, page 24, and personal letter). Wisconsin drift covers the northeastern part of the State (Leverett, 1899, page 24; 1915, page 62; Leighton, 1923, page 268). Leighton now refers the drift of the Green River lobe to the early Wisconsin.

MISSOURI

In Missouri three separate drift sheets, which form soils, have been differentiated by Leverett, who has supplied their borders for the maps. The youngest drift is Illinoian, which is found just below the mouth of the Missouri. North of the Missouri and west of the Mississippi Kansan drift constitutes the soils. The border is a revision of that outlined by Leverett in 1915 (page 503).

From the junction of the Mississippi with the Missouri for nearly 125 miles downstream there is an old drift, which is correlated with the Jerseyan, and is thus of Kansan or Nebraskan age (Leverett, 1924, and personal letter). South of the Missouri, in the central and western parts of the State, there are also scattered erratics that may be remnants of an old till, probably of Nebraskan age (Leverett, 1923, and personal letter).

KANSAS

The northeastern part of Kansas contains glacial drift. As no trace of an older drift has been observed in the region where it might be expected—that is, north of Kansas River, Dr. Schoewe, according to information received, now hesitates to refer highly weathered fragments

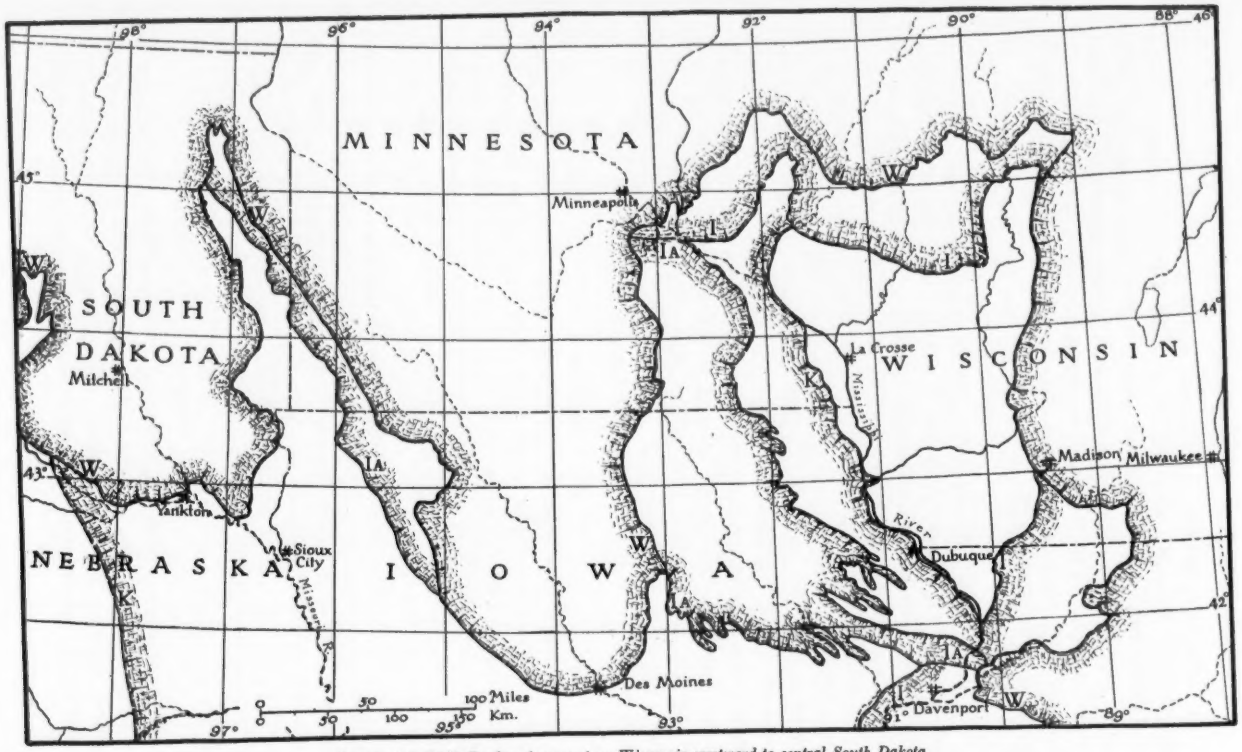

FIGURE 5.—*Drift Borders from eastern Wisconsin westward to central South Dakota*
K, I, Ia, and W designate the Kansan, Illinoian, Iowan, and Wisconsin drift sheets. Scale, 1 : 5 million.

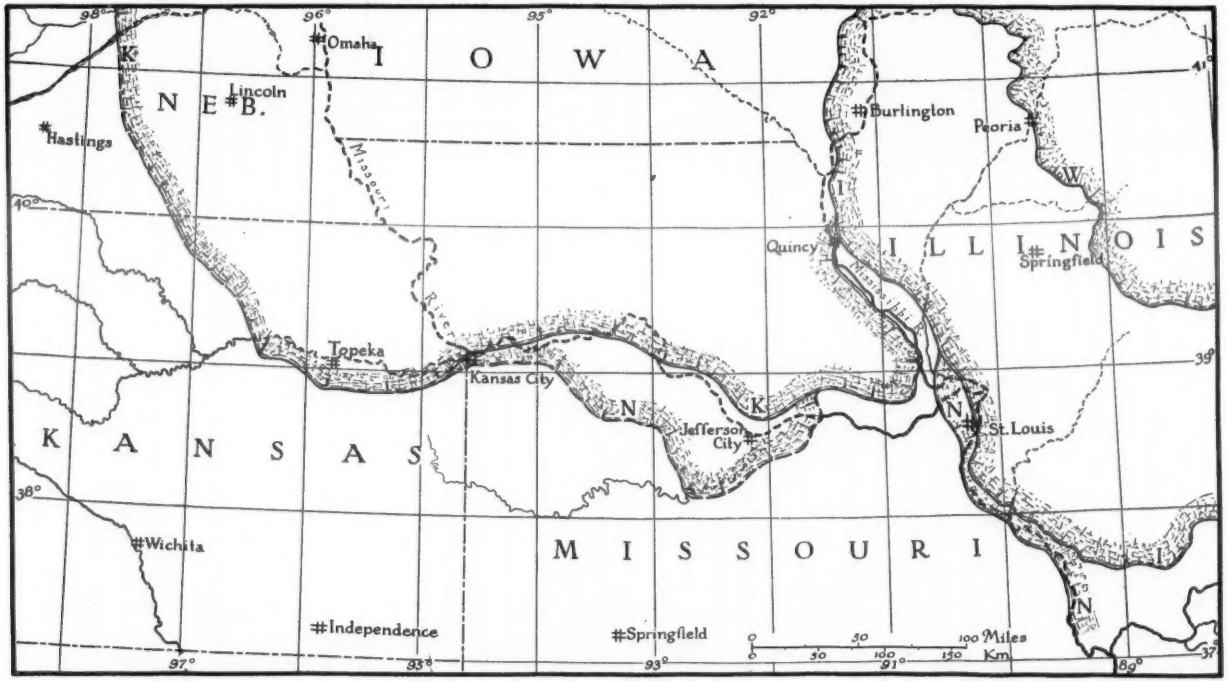

FIGURE 6—*Drift Borders from eastern Illinois westward to central Nebraska*
N, K, I and W designate the Nebraskan, Kansan, Illinoian, and Wisconsin drift sheets. Scale, 1 : 5 million.

of chert and quartzite found outside the previously mapped Kansan ice-border to the Nebraskan. He is inclined to refer all drift so far known to the Kansan glaciation. The drift border south of Kansas River, as here given, has been fairly well established by Schoewe (1928, 1928*a*, 1929), but that north of the Kansas River, kindly supplied by him, is only tentative (cf. Schoewe, 1923).

NEBRASKA

The Pleistocene ice reached only the eastern part of Nebraska. The surface drift, according to Leverett, may be of Kansan age. The boundary given is that fixed by Condra (1908, page 47). Nebraskan drift probably occurs under the Kansan at the east end of the State (Leverett). According to a recent statement by Prof. Condra the surface drift in his opinion is of Nebraskan age.

IOWA

In northeastern Iowa there is an old drift, probably of Kansan age, which extends eastward to the driftless area on the Mississippi (Leverett). A considerable part of northeastern Iowa is covered by Iowan drift, whose border in the northern part of the State, where it is fairly well defined, has been determined by Kay (1928, page 510), and whose border in the southern part, where it is defined only approximately, has been furnished by Dr. Alden (also Alden and Leighton, 1915, pages 122, 177-181). In northwestern Iowa there is a belt of Iowan deposits (Leverett, 1922*a*). The central-northern part of the State, down to Des Moines, is covered by deposits of the Wisconsin glaciation. The southern and western parts bear Kansan drift, whose outer border lies in Missouri and Kansas. An older general glacial map is given by Leverett (1915, page 503).

WISCONSIN

A region that includes southwestern Wisconsin, a small adjoining area in northwestern Illinois, and a narrow strip in Iowa and Minnesota is remarkable for its lack of all drift. This region, known as the driftless area, presents ancient erosional remnants, which show that it was at no time during the Ice Age invaded by ice. The contrast between this region and the surrounding regions was first recognized in 1823 (Martin, 1916, page 73).

All the drift borders in Wisconsin, as shown on our maps, have been supplied by Leverett (cf. Leverett, 1915, pages 62, 503; 1922*a*). A pre-Illinoian drift that forms the western boundary of the driftless area is possibly of Kansan age. Illinoian drift is found south of Madison.

The bulky Marshfield moraine, which runs 15 to 20 miles north of the driftless area, is also of Illinoian age. Though the evidence is not clear, the Illinoian drift probably extends beyond this moraine down to the unglaciated area. The surface deposits in the eastern and northern parts of the State are Wisconsin drift.

MINNESOTA

The material for the maps of Minnesota has been supplied by Leverett (cf. Leverett and Sardeson, 1919; Leverett, 1922*a*). All the drift sheets in Minnesota except the Nebraskan appear to be represented in the surface soils. A very old drift, probably Kansan, in the southeastern part of the State, forms the glacial limit toward the driftless area. The same drift is found also in the southwestern corner of the State. Illinoian deposits cover a small area a little south of Saint Paul. Iowan drift forms surface beds in belts in the southeastern and southwestern parts of the State. The boundary indicated for the Iowan drift in southeastern Minnesota is only tentative. These several drift sheets and the small non-glaciated region in the southeastern corner of the State occupy only a small area, almost the entire State being covered by deposits laid down during the Wisconsin glaciation.

SOUTH DAKOTA

Deposits of three separate glaciations are recognized among the surface soils in South Dakota. Kansan drift is found in the eastern part of the State outside other drift borders. Iowan drift occurs in a narrow strip in the northeastern part of the State (Leverett, 1922, 1922*a*), and, according to Alden, is represented by a broader belt in the north-central part. Wisconsin drift, represented by a remarkable lobe, a counterpart of the still larger Des Moines lobe in Minnesota and Iowa, covers practically all the eastern part of the State. Its eastern border is given according to Leverett, its western according to Johnson (see Visher, 1918, page 34).

NORTH DAKOTA

In North Dakota two drift sheets form the surface soils (Leonard, 1916; 1919; 1926, page 24; Alden, 1924, page 387). One, the Wisconsin drift, covers roughly the part of the State lying northeast of the Missouri River. The other extends some 50 miles southwest of the Missouri. The age of this drift is not definitely determined. Alden is inclined to regard it as Iowan, but Leonard, with reservation, refers it to the Kansan.

MONTANA

In northeastern Montana the same two drift beds that are seen in North Dakota are represented, probably the Wisconsin and the Iowan.

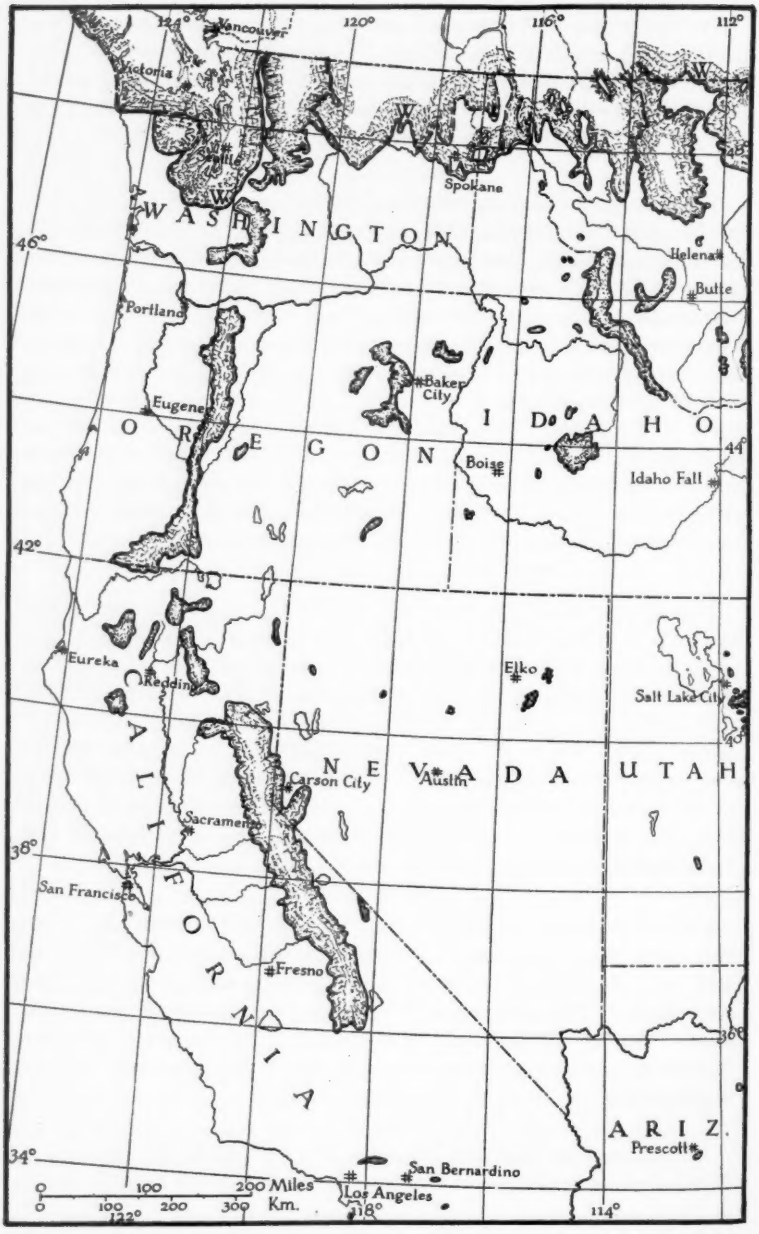

FIGURE 7.—*Pleistocene Mountain Glaciation and Borders of Ice-sheets in southern Canada and United States West of the 112th Meridian*

Ia and W indicate Iowan and Wisconsin drift borders. Mountain glaciation undifferentiated and unlettered. Equal area projection. Scale, 1 : 10 million.

FIGURE 8.—*Pleistocene Mountain Glaciation and Borders of Ice-sheets in the Rocky Mountain and Great Plains Regions of the United States*

K, Ia, and W indicate Kansan, Iowan, and Wisconsin drift borders. Mountain glaciation undifferentiated and unlettered. Equal area projection. Scale, 1:10 million.

The drift borders here given are those determined by Alden (1924, plate 11), who has revised the glacial map prepared by Calhoun (1906, plate 1). The Wisconsin ice-sheet extended more than 100 miles south of the International Boundary. It was not thick enough to overtop the Sweetgrass Hills.

In northwestern Montana, on the other hand, only one drift is distinguished; and its age is not known. Its border, as mapped by Pardee (1910, page 382), probably agrees best with the border of the Spokane drift, as mapped by Anderson (1927, plate 1), in the adjoining region to the west. The Spokane drift, according to Alden, should probably be correlated with the Iowan. The drift border here has therefore been marked "Iowan or Wisconsin." A few high areas formed nunataks.

IDAHO

In northern Idaho a Wisconsin and a Spokane drift, each laid down by the continental ice-sheet, are distinguished (Anderson, 1927, plate 1). The Spokane drift, according to Alden, may be a correlative of the Iowan drift of the Middle West. The Spokane ice covered most of the narrow northern part of the State, leaving only a few small areas free. The Wisconsin ice sent down long lobes only in the main valleys.

WASHINGTON

In northern Washington Spokane and Vashon (Wisconsin) drift sheets are recognized. The Spokane drift, according to Alden, should probably be correlated with the Iowan. The Spokane border has been mapped through Spokane west-northwestward to the Columbia River (Bretz, 1928, plate 5). Here it seems to disappear under the Wisconsin drift. At about latitude 47° 50′ north, longitude 119½° west, its border inside the Wisconsin boundary has been relocated by Bretz.

The Wisconsin drift border in the eastern part of Washington is compiled from data supplied by Stewart (1913, page 428), Pardee (1918, page 51), Anderson (1927), Bretz (1928), Salisbury (1901, page 722), and Russell (1900, page 169). Its course is not well known. In the Cascade Mountains there was a network of glaciers that was more or less confluent with the ice-sheet. The differentiation between these glaciers and the ice-sheet, especially on the east side of the mountains, is difficult to determine from the data now at hand. The course of the drift border west of the Columbia River is unknown. On the west side of the Cascades the extreme limit of the last ice-sheet, the Puget Sound Glacier, is somewhat better known. On the lowland of Puget Sound and farther west the limit of the last continental glacier is satisfactorily established (Leighton, 1918; Bretz, 1920).

BRITISH COLUMBIA

On Vancouver Island the remains of two glaciations have been observed, Admiralty drift and Vashon drift, which are separated by Puyallup interglacial deposits (Clapp, 1913, pages 9, 20, 116; 1917, pages 17, 25, 63, 263). The Vashon glaciation is the last one, and it may correspond to the Wisconsin glaciation of the east. The Admiralty glaciation is of unknown age. During the first and most intense glaciation the island was covered by a thick ice-cap, which rounded all the mountains that stood less than 4,000 or 5,000 feet high. Glaciers occupied and scoured out the larger valleys, converting some of them, chiefly the valleys running southwestward, into fjords, and eventually coalesced, ending in the outer part of the present skerry-guard (G. M. Dawson, 1880, page 99). The valley glaciers that flowed eastward from the main mountain range joined the larger glaciers that descended from the ranges of the mainland and formed an extensive piedmont glacier, which occupied the lowlands and the Georgia Strait and buried the islands in the strait.

During the later, far less severe, Vashon glaciation an unknown part of Vancouver Island was covered by ice. The glacial deposits north of Vancouver Island have not been differentiated as to age. During its greatest extent the ice probably reached the open sea off the skerry-guard (G. M. Dawson in W. Dawson, 1893, page 286). Queen Charlotte Island probably formed a separate center of glaciation. On account of their rather small gathering ground, the glaciers here were shorter. In Graham Island the Queen Charlotte range at least was covered by an ice-cap, from which glaciers descended the valleys, scouring out the fjords (MacKenzie, 1916, page 117). The wide distribution of glacial deposits show that the ice also spread over the lowlands, though it did not reach the northern shore.

ALASKA

Although American geologists have done excellent work in Alaska, the glacial geology of that vast, remote, and inaccessible region is but little known. The drift sheets that may occur there have not been differentiated. The areas covered by Pleistocene glaciers are fairly well known, but their borders have not been outlined in detail. The boundaries here given are those supplied by the United States Geological Survey to Tarr and Martin (1914, map 1; compare Brooks, 1906, page 244, plate 22), locally improved after later reports (Leffingwell, 1919, pages 133, 141; Mertie, 1928, page 118; Capps, 1929, page 90; Knappen, 1929).

The Pleistocene glaciation in Alaska was confined to the mountains and the adjacent parts of the lowlands; the great central plain and the lowlands of the Bering Sea and the Arctic Ocean were free from Pleistocene glacial ice. These facts show that heavy precipitation as well as low temperature is essential to severe glaciation. Considerable tracts in the mountains rose above the ice-caps (Brooks, 1906, page 244; Gilbert, 1904, page 141). The ever-present large and small fjords on the Pacific coast of Alaska were doubtless in part carved out and largely shaped by Quaternary glaciers, which joined to form a system of separate piedmont glaciers or a confluent piedmont glacier that probably covered the entire skerry-guard except the high ranges and summits. Thus, in Kenai Peninsula, the ice extended beyond the position of the modern coastline, and it seems to have covered Kadiak Island with a practically continuous sheet, through which scattered peaks projected as nunataks (Gilbert, 1904, pages 177, 181). On Alaska Peninsula the glaciation was less intense. Here valley glaciers pushed down the existing stream valleys and spread out on the plains bordering the Pacific Ocean and Bering Sea (Knappen, 1929). In the Aleutian Islands, also, the ice was made up of separate alpine glaciers.

On the islands in Bering Sea no traces of Pleistocene glaciers seems to have been observed (Gilbert, 1904, pages 186-192).

ARCTIC NORTH AMERICA

The Pleistocene glaciation in Arctic North America is naturally far less known than that in other parts of the continent. According to Chamberlin's map of 1913 the whole Arctic Archipelago was glaciated at some time. According to the maps of Schuchert (1914, page 266) and Alden (1924, page 32), on the other hand, fairly large parts of it were free from ice. Baffin Land, Melville Peninsula, and Southampton Island seem to have been entirely buried beneath ice (Freuchen and Mathiassen, 1925, pages 552, 555, 560; also Gould, 1928). As the evidence in these areas includes striæ, the glaciation may have been synchronous with that of the last ice-sheet. Leverett informs me that, according to Knud Rasmussen, the northern limit of the Pleistocene ice-sheets in the Mackenzie River district stood below latitude 68 degrees north and east of that district below latitude 70 degrees north, or just north of Coronation Gulf. The modern presence of ice-caps and glaciers indicate that Prince Patrick Island, East Sverdrup Island, Ellesmere Land (Weeks, 1927), and Grant Land were glaciated. On the south shore of North Devon Island, in latitude 75° north, longitude 85° west, there are traces of a slightly more widespread glaciation during the Pleistocene than at present (Low, 1906, page 233). At the head

FIGURE 9.—*North America*

Areas glaciated during the Pleistocene. Equal area azimuthal projection. Scale, 1 : 60 million.

NOTE. The entire mainland between the Mackenzie River mouth and Coronation Gulf, longitude 114° west, was glaciated.

of Liddon Gulf, Melville Island, in latitude 75° 15′ north, longitude 110° 30′ west, there have been observed striæ of a former local glacier (McMillan, 1910, pages 411, 461). Since the maps were drafted I find that O'Neill (1924, page 34A) observed striæ at several localities on the

coast between Darnley Bay and Kent Peninsula, a fact suggesting that the entire mainland from the mouth of the Mackenzie River eastward to Coronation Gulf was covered by ice during the Pleistocene.

LABRADOR

The high tableland and the summits of the Torngat Mountains, in northeastern Labrador, show no evidence of glacial action (Coleman, 1920, page 320; 1921, page 26). The driftless area can not yet be exactly outlined, but along a coastal belt that extends from Saglek, in latitude 58° 30′ north, to Komaktorvik, in latitude 59° 30′ north, a distance of 80 miles, there are no indications of the action of ice above the valleys. At Nachvak the unglaciated area reaches at least 50 miles inland. Except for the areas mentioned, all the land in Labrador may have been glaciated.

GULF OF SAINT LAWRENCE

There appear to be traces of two or three Pleistocene glaciations in Newfoundland (Coleman, 1926; Lundberg, 1929, page 97). During the oldest (Kansan or Jerseyan) glaciation, recorded by deeply weathered till and erratics, the entire island except the southern part of the Long Range was overswept by ice from Labrador (Coleman, 1926, page 220; 1927, page 401). If there were three glaciations, the extent of the second is practically unknown, for it seems probable that the striæ preserved derive from the last (the Wisconsin) epoch. The areas of the last glaciation as shown on our map have been determined largely from striæ. The Labrador ice-sheet may have reached the northwestern part of the Strait of Belleisle, where striæ have been observed. The Wisconsin ice probably covered less than half of Newfoundland and was in the form of small separate caps and glaciers, which were greatly influenced by the local topography. According to Lundberg, one center of ice stood just north of Red Indian Lake, from which the ice flowed southward as well as northward. The tablelands of the Long Range were not glaciated.

Fresh, distinct traces of glacial action show that the low island of Anticosti may have been completely buried beneath the last ice (Twenhofel, 1928, page 9).

An area about 50 miles long and 10 miles broad in the higher country of the interior of Gaspé—that is, the higher parts of the Shickshock Mountains—seems never to have been touched by Quaternary ice (Coleman, 1920, page 323; 1922; Alcock, 1926, page 23). The ice-sheets were too thin to cover the high mountains, and the local glaciers that radiated from the range did not form above 3,500 or 4,000 feet.

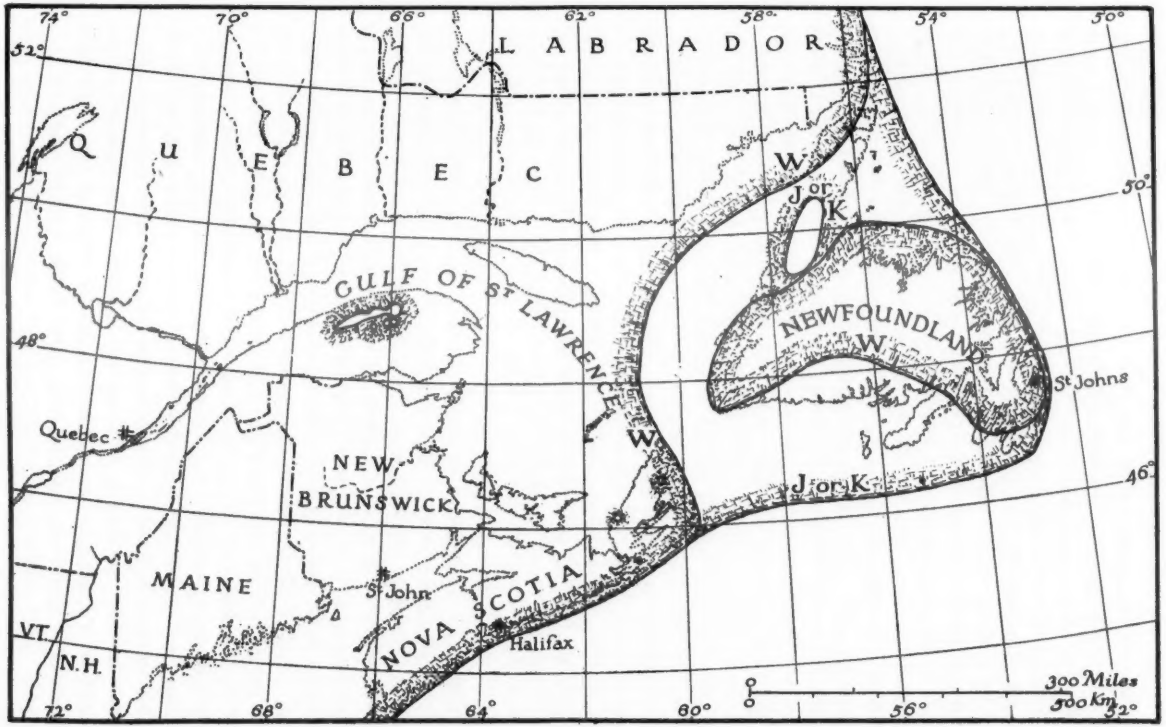

FIGURE 10.—*The most extensive Glaciation (Jerseyan or Kansan) and the last Glaciation (Wisconsin) on the Gulf of Saint Lawrence*
J or K designates Jerseyan or Kansan and W Wisconsin glaciation. Scale, 1 : 10 million.

The lower parts of Prince Edward Island may have been reached by ice; the interior, which rises but little over 300 feet (90 meters), has not been well studied (Coleman, 1920, page 322).

On the Magdalen Islands, Goldthwait (1915) found till containing well-striated stones up to a height of 105 feet. Hills carrying loose blocks, thus lacking evidence of glacial action, rise in places to 360 feet. Coleman (1927, page 402) thinks that the drift on these islands was produced by the most extensive glaciation; but as there are southeasterly striæ on the west coast of Cape Breton Island, Nova Scotia, and as most of this island was buried beneath ice coming from the northwest (Goldthwait, 1924, map), the till in the Magdalen Islands is probably of Wisconsin age. The last ice-sheet thus seems to have filled the western part and the shallow southern part of the Gulf of Saint Lawrence, but it may have broken off in the deeper water of the central and eastern parts.

No sure evidence of more than one (the last) glaciation has been obtained in Nova Scotia (Goldthwait, 1924, page 102). Ice from the Labrador ice center then moved across the island eastward and southeastward until it reached the sea, as shown by numerous striæ on the east coast (Goldthwait, 1924, map). This ice-sheet may have covered nearly all the land. In Cape Breton Island the northern tableland—that is, the northernmost point of Nova Scotia,— the Mabou Highlands, in latitude 46° 10′ north, 61° 25′ west, and probably some other high flat areas rose above the ice-sheet (McIntosh, 1928).

GREENLAND

Greenland is now buried beneath a thick sheet of ice except in a coastal belt. This belt is at some places rather wide, at other places is narrow, and at still other places is broken through by broad glaciers. During the Pleistocene epoch the ice was of still greater extent. How many times the area of ice expanded is not known, but it did so at least twice (Hobbs, 1927, pages 15-18). During the first expansion the ice probably covered all the land. In the Holstensborg district, in latitude 67° north, 53° 40′ west, the ice then reached the sea, as is shown by roches moutennées, by rare occurrence of polished pavement, and by erratics, none of which reveal distinct glacial faceting or striation.

During the second expansion the ice in the Holstensborg district halted when it had reached a position about halfway between its present limit and the sea—that is, within some 50 miles (80 kilometers) of the coast—as is shown by fresh traces of glacial action in this inner belt. The outer region is rugged and more than 1,000 feet (300 meters) high, but the inner region is only hilly and was worn down by ice erosion to about two-thirds of the height of the outer belt.

In other parts of Greenland the action of separate Pleistocene ice-sheets has not been distinguished. Even during the greatest extent of the ice there may have been many high mountain summits that towered above it (Koch, 1926, page 104; Antevs, 1928, page 78). The areal extent of the nunataks, however, may have been small. Of more value is the observation made by Koch (1926, page 105), that the ice-sheet never covered the northern part of Peary Land. The limit of the ice-sheet is marked by a large belt of moraines. Although local glaciers descended the high alps of northern Peary Land, large areas may have been free from ice.

Pleistocene Glaciations in the Mountains of the United States and Mexico

Traces of local Pleistocene glaciers outside the continuous ice-sheet in the United States east of the Rocky Mountains have not been found, but on the western mountains there were numerous glaciers, some of them large, as well as networks of glaciers and ice-caps. Glaciers were formed, of course, primarily in the Rockies, the Cascades, and the Sierra Nevada, but also in several other ranges. See Figures 7 and 8.

The outlines of some of the glaciers and ice-fields are satisfactorily mapped, but those of most of them are not. By some observers the traces of glaciation are merely described; by others they are mapped only when the bedrock underlying the drift is not known. The actual extent of the former ice in many areas being thus little known, the scattered data of glacial action have been compiled and probable generalizations have been made from them. In compiling our maps original literature and geological and topographical maps, as well as earlier compilations, have been used. Among these latter Chamberlin's (1913) wall-map and Louis' (1927) map deserve special mention.

For many areas the age of the mountain drift has not been determined, but at places distinction has been made between drift of two or three ages. The first observations of repeated mountain glaciation were made at the beginning of this century. Then Salisbury and Blackwelder (1903) found traces of two or perhaps three separate glacial epochs in the Bighorn Mountains of Wyoming, and Hershey (1903) presented evidence of two epochs of glaciation in the Klamath Mountains, on the boundary between Oregon and California. The ground having thus been broken, similar observations were made in many mountains. Two stages of considerable mountain glaciations have been observed in Colorado on the Sangre de Cristo Range, in latitude 38 degrees north, longitude 105° 30′ west (Siebenthal, 1907, page 22); at Georgetown, due

west of Denver (Ball, 1908, page 84; Bastin and Hill, 1917, page 58), and in the Rocky Mountains National Park, northwest of Denver (Lee, 1917, page 31); and three stages have been distinguished in the Sawatch Range, in latitude 39 degrees north, longitude 106° 30′ west (Capps and Leffingwell, 1904), and in the San Juan Mountains, in latitude 37° 40′ north, longitude 107° 30′ west (Atwood and Mather, 1912). In the Uinta and the Wasatch Mountains, east of the Great Salt Lake, in Utah, drift of two epochs have been differentiated (Atwood, 1909). The older drift in these mountains is the most extensive and, according to Alden, is probably of Iowan age; the younger drift is correlated with the Wisconsin glaciation.

In the high mountains of central Idaho there is a very old drift (Ross, 1929). Patches of similar drift, regarded as Nebraskan or Kansan, are found outside the Wisconsin deposits in the mountainous regions of Montana (Alden, 1924, page 387; Jeanne Russel, 1926). Drifts of three different ages seem to occur in the Beartooth Mountains, just northeast of the Yellowstone National Park (Bevan, 1927). Two glaciations, an extensive one in early Pleistocene (Admiralty) time, and a smaller one in late Quaternary (Wisconsin) time, are on record in the Cascade Range of Oregon (Hodge, 1927). In the Yosemite region, California, evidences of three glacial epochs have been discovered (Matthes, 1928). The latest may be correlated with the Wisconsin glaciation. On the east side of the Sierra Nevada, three and probably four distinct epochs of glaciation can be recognized (Blackwelder, 1929). The San Gabriel Mountains at Los Angeles may have been glaciated early in Quaternary time (Miller, 1926).

In some areas the deposits laid down during different glaciations have been mapped separately, but it has not been possible to represent these deposits separately on our maps, which show in a general way the extent of the areas that are known or held to have been covered with ice at one or more times during the Quaternary.

Local glaciers and ice-fields were formed in the Rocky Mountains at favorable places from the Canadian boundary southward to Santa Fe, New Mexico, in latitude 35° 45′ north. Glaciers were particularly numerous and large in northwestern Montana, on the border between Montana and Idaho, in the Yellowstone Park region, and in Colorado. The Bighorn Mountains of Wyoming formed a notable center of glaciation. Other centers were in the Uinta Mountains of Utah and in the mountain ranges bordering the Great Basin on the northeast and the north. In the Great Basin itself glaciers were naturally both scarce and small.

The Cascades and the Sierra Nevada seem to have supported an almost continuous network of glaciers. The mountain glaciers in southern California were probably the southernmost in the United States, for the supposed traces of glacial action at Nogales, on the boundary between Arizona and Mexico, are doubtful (D. Johnson, 1910, page 219). Pleistocene glaciers were formed also at Prescott and Flagstaff, in central Arizona.

Glaciers were formed on Ixtaccihuatl and Popocatepetl, southeast of Mexico City (Jaeger, 1926), mountains that are snow clad today.

Ice-Sheets in northern Europe

SCANDINAVIA

Deposits containing temperate biota between drift beds in the peripheral zones of the glaciated areas do not necessarily mean that the ice-sheets had completely vanished. Similar deposits found in the central parts of glaciated areas are significant, however, and are therefore of particular interest. The great erosive power of the last ice-sheet in its central parts left few unconsolidated beds that were laid down during earlier glaciations. Several conditions in Scandinavia suggest two Pleistocene glaciations and one interglacial epoch, yet perhaps only the gyttja on Hernön, in latitude 62° 35′ north, longitude 18° east, a mile south of Hernösand (Munthe, 1904, 1909, 1909*a*), furnishes conclusive evidence. The gyttja lies in the very center of the former Scandinavian ice-sheets. The section on Hernön is—

Bouldery till, 2.5 to 5 meters thick, at top.
Sandy, fresh-water gyttja, fossiliferous, 0.7 to 3 meters thick.
Sand and gravel with glaciated cobbles.

The gyttja contains remains of animals, notably of insects, and numerous remains of plants, all suggesting a temperature somewhat like that of today or slightly lower. The interglacial age of the gyttja is shown by the fact that it lies only 5 meters above sea level and that it is a fresh-water deposit, whereas the shoreline of the Baltic only recently retreated below this level, and the Gulf of Bothnia, close to which the gyttja occurs, is brackish.

A mile and a quarter west-southwest of Bollnäs, in latitude 61° 20′ north, longitude 16° 20′ east, small lenses of a dark, sandy, fossiliferous gyttja were found in till from 6 to 8.5 meters below the surface, which lies 96 meters above sea level (Halden, 1912). The gyttja contains remains of numerous plants, some of which suggest a slightly higher temperature than that which now prevails in the region. The gyttja

FIGURE 11.—*Western Europe*
Areas glaciated during the Pleistocene. Equal area azimuthal projection. Scale, 1 : 25 million.

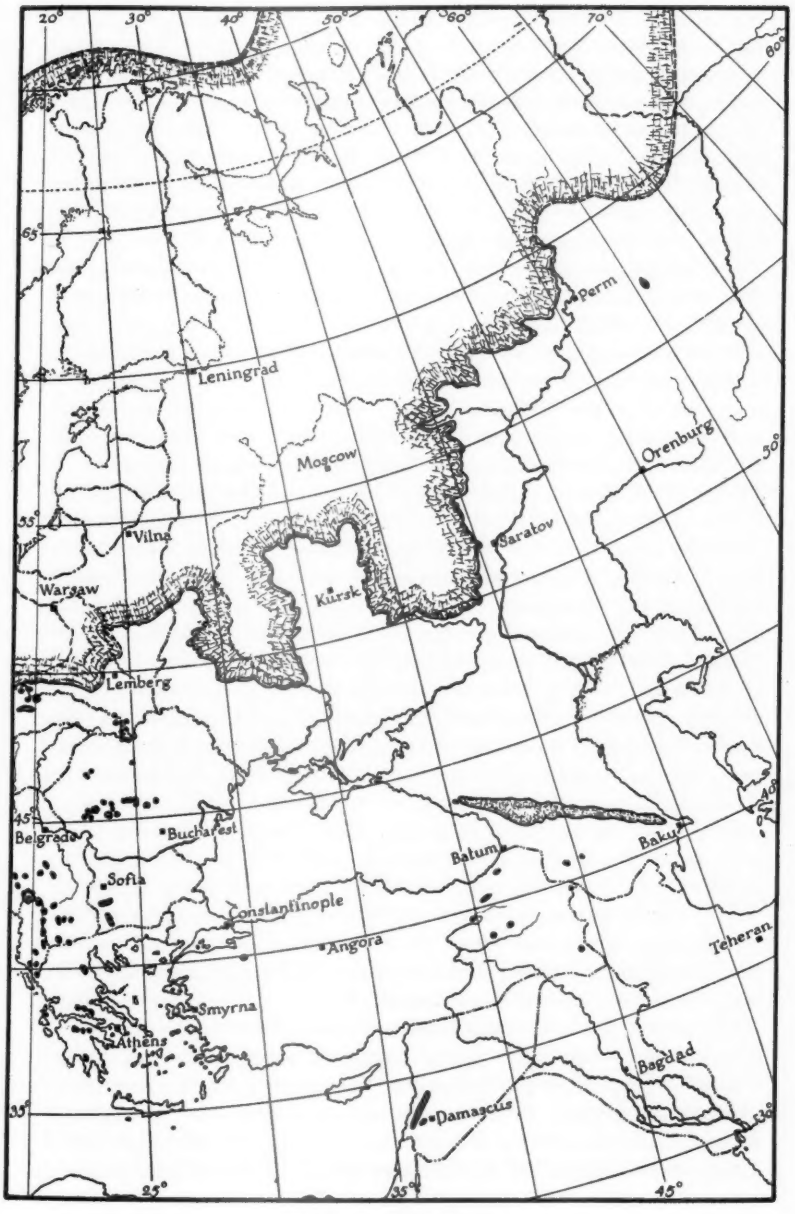

FIGURE 12.—*Eastern Europe*
Areas glaciated during the Pleistocene. Equal area azimuthal projection. Scale, 1 : 25 million.

was found in a hummock of till and is possibly postglacial, for the till may have slidden down.

Supposed interglacial deposits in Norway are of doubtful significance, and some of them lie near the border of the last glaciation (Björlykke, 1913, page 129; Holmsen, 1924, page 10; Öyen, 1929). More significant, probably, is a river gorge at Rjukan Foss, in southern Norway, in latitude 59° 52′ north, longitude 8° 30′ east, which is cut down in the bottom of a glacial trough and shows by glacial striæ and smoothing that it is of interglacial age (Ahlmann, 1919, pages 28, 29, 145).

During one or more periods of glaciation the entire Norwegian mainland, as well as all the bordering islands, may perhaps have been completely buried beneath ice.

Few traces of separate Pleistocene glaciations have been observed in northern Norway, but most of the drift and other glacial features have been referred to the last glacial epoch. North of Vesterålen, in latitude 69 degrees north, only scattered observations have been made regarding the extent of the glaciations. During the last epoch, according to Tanner (1915, page 132), ice covered all the land and extended far out in the shallow-water belt, but Grönlie (1927, pages 54, 56), believes that it was far less extensive. According to Grönlie, ice covered the eastern part of Finnmark Fylke and all the plateau lands, but in the coastal belt, from the Porsangen, in latitude 71 degrees north, longitude 26 degrees east, to Vesteralen it only filled valleys, fjords, and sounds, the high intervening land areas having been more or less free from ice. In Vesterålen and Lofoten the extreme border of the ice-sheet ran through Andöy southwestward to Austvågöy and thence west-southwestward along the inner edge of Vestvågöy, beyond which it lay in the sea. On the Arctic Circle an ice-sheet extended all the way out to Træna, in latitude 12 degrees east, but as only huge boulders have been found in that region it may have been an old ice-sheet (Rekstad, 1925, page 35). The last ice-sheet must have reached out to Lovundvær, in latitude 66° 25′ north, longitude 12° 25′ east, and Åsvær, in latitude 66° 15′ north, longitude 12° 20′ east, where glaciated ledges are found.

The extent of the ice-sheet on the northwest coast is not well known. The islands and peninsulas west and southwest of the Trondhjemsfjorden may or may not have been reached by the ice. According to Ahlmann (1919, page 212), the extreme border ran from the mouth of the Trondhjemsfjorden southwestward to a point just north of Ålesund, in latitude 62° 30′ north, longitude 6 degrees east, leaving a belt of peninsulas and islands outside. Recently a moraine that may mark the extreme limit of the ice is reported to have been found in the outermost part of Fröya, in latitude 63° 45′ north, longitude 8° 40′ east (Dons, 1928).

On the west coast of Norway the ice seems to have reached out into the sea, but it was probably so thin that many islands and high peninsulas rose above it and formed places of refuge for arctic plants and animals (Björlykke, 1913, page 133; Antevs, 1928, page 26).

SHETLAND ISLANDS

The Shetland Islands appear to have been completely covered by ice that moved in general from east to west (Peach and Horn, 1879). No Scandinavian boulders have been found, but the direction of the numerous striæ and roches moutonnées, which occur on the east as well as on the west coasts, shows that the ice came from Scandinavia. During a later stage, or more probably during a later glaciation, the islands carried valley glaciers that radiated in all directions from the highlands, as is suggested by another set of striæ. No boulders from Scotland seem to occur.

BRITISH ISLES

The number and the extent of the Pleistocene glaciations in the British Isles are debeted. The elaborate system of glaciation given by Geikie (1895, 1914) seems to have no basis in observations (Kendall, 1917, page 310; Charlesworth, 1928, page 325). The belief of Lamplugh (1906, 1914), that there was but one glaciation, represents another extreme view. A decade ago two glacial epochs were usually distinguished in England (Wright, 1914, page 79; Kendall, 1917, page 310). Now three glacial epochs are distinguished by most geologists from as many sheets of boulder clay (Kendall and Wroot, 1924, page 475; Keith, 1925, pages xv, xvi; Pocock, 1925, page 38; Gregory, 1925-26, pages 370-75). Kendall and Wroot tentatively correlated these drift sheets as follows:

England	The Alps	North America
Hessle Clay	Würm	Wisconsin
Purple Clay	Riss / Mindel	Iowan / Illinoian
Basement Clay	Günz	Kansan

As the longest interglacial epoch may fall between the Mindel and the Riss glaciations, Kendall and Wroot may mean that the Purple Clay should be correlated with either the Mindel or the Riss. Keith correlates the British boulder clays with Günz, Mindel, and Würm; Pocock correlates them with the Mindel, Riss, and Würm; and Gregory correlates the first two with the Riss and third with the Würm. The British glaciations probably correspond to the Mindel, Riss, and Würm. The oldest drift is probably of wider extent than the last (Kendall and Wroot,

1924, page 471), and the second may be the most widely distributed, although Pocock (1925, page 38) thinks that the first has the widest distribution, and Sandford (1929, pages 382-83) refers the outermost drift in the Oxford district to the first glaciation (Mindel?). The oldest drift sheet has not been regionally well separated from the second and is not mapped. The peripheral drift perhaps derives here from the first glaciation, there from the second.

The oldest drift occurs in Yorkshire. The drift on the east coast contains many boulders derived from the Oslofjorden (Wright, 1914, pages 51, 63). The extent of the second glaciation also is unknown, though it may almost coincide with the outermost border of drift shown on the map. During this glaciation the ice-sheet may have covered all of Great Britain down to the Thames Valley and the Bristol Channel except some mountain ranges. The southern boundary is sketched from a map of the glacial drift given by Harmer (1928, plate 5; see also Wright, 1914, page 49). In the Pennines, east of Manchester (Woodhead, 1929, page 7) and at the heads of the rivers Tees, Wear, and South Tyne (Wright, 1914, page 72; Kendall and Wroot, 1924, page 476), as well as in the Cleveland Hills, halfway between Hull and Newcastle (Wright, 1914, page 71; Kendall and Wroot, 1924, page 491), there are areas that were not reached by the ice. According to Jowett and Charlesworth (1929, pages 316, 334) only little of the area south of the Peak in the Southern Pennines was ice-free.

According to Harmer's map, no drift is found on other mountains, such as most of those in Wales and those east of Morecambe Bay, but whether Harmer means that they were unglaciated or that the drift has not yet been observed is not evident. The Welsh Mountains, according to Geikie (1895, page 381) raised their summits considerably above the general level of the ice-sheet.

In Scotland the lower ranges of hills, such as the Sidlaws, the Ochils, the Pentlands, the Kilbarchan and Paisley Hills, and the Cheviots, exhibit polished and smoothed rock faces on their very crests, and the action of ice in their central parts is traceable up to an elevation of at least 3,500 feet (1,070 meters); so that all the land except the higher mountains was buried beneath a mer de glace (Geikie, 1895, pages 60-68). Ice filled up the shallow seas around Great Britain down to the Thames and the Bristol Channel.

The Orkneys were overridden by ice from northeastern Scotland, which was deflected from its northeasterly course by ice from Scandinavia and the North Sea (Peach and Horn, 1880), as shown by striæ, roches moutonées, and Scottish boulders. No Scandinavian erratics have been observed. Striæ are numerous in all parts of the islands.

FIGURE 13.—*Drift Borders in the British Isles*

Older and middle (probably Mindel and Riss) drifts and newer (Würm) drift. Scale, 1 : 7.5 million.

NOTE.—Since the drafting of this map the border of the newer drift in England and Wales has been shown in greater detail on a map by Charlesworth (1929*a*, page 336).

After the Scotland-North Sea ice had waned, i. e. probably during a later epoch, there were alpine glaciers in the valleys of Hoy and in some of the higher parts of the mainland. The glacial history of the islands is therefore parallel to that of the Shetlands.

The Scottish ice pushed westward until it broke off in the deep water beyond the edge of the continental shelf. The Hebrides, except the very highest mountain tops, were covered (Geikie, 1895, page 82). The glaciation included the Isle of Man, which was completely covered (Geikie, 1895, page 377). The Scottish-English ice-sheet coalesced with the Irish ice, which probably covered all of Ireland except the tops of the higher mountains (Geikie, 1895, page 415; Charlesworth, 1928, pages 319, 321).

On the British coast of the North Sea, from a point 25 miles south of Norwich to Newcastle, and at Aberdeen, in Scotland, the till contains boulders brought from the Oslofjorden (Harmer, 1928, plate 5; Wright, 1914, pages 51, 63; Read, 1923; Bremner, 1928, page 163). These foreign rocks spread landward to Cambridge, the west side of Lincoln Wolds, and the northwest side of the Cleveland Hills. The Scandinavian boulders are more numerous in the oldest drift than in the second, so that it is not known whether those in the second till bed were derived from the oldest till or whether ice brought over boulders directly from Scandinavia during the second British glaciation as well as during the first. When they were brought over, however, ice coming from Scandinavia met the British ice on the coast of the North Sea, north of the Cleveland Hills, deflected it, and encroached upon the British coast.

The last glaciation, corresponding to the Würm in the Alps and the Wisconsin in North America, affected Scotland, northernmost England, Wales, and the east coast to a point south of the Wash (Wright, 1914, page 76; Kendall and Wroot, 1924, pages 476, 491; Woodhead, 1929, page 9). This epoch of glaciation may be the equivalent of the third glacial epoch of Geikie (1914, map C). The outer border of the ice-sheet is not well known, nor its upper border against the mountains, but the nunatak areas that existed during the second glaciation must have been larger, and there were probably others. The numerous striæ in the Hebrides (Geikie, 1895, plate 4, page 158) perhaps show that these islands also at this time were overrun by ice from Scotland. Since the drafting of our maps, a map purporting to show in some detail the outer limit of the newer drift has been published by Charlesworth (1929*a*, page 336).

The extent of the ice in Ireland during the last glaciation is well known through a recent study by Charlesworth (1928). The continuous mer de glace that buried the northern part of the country reached down to a curved line running from the mountains south of Dublin to the mouth of the Shannon. Outside of this great glacier smaller glaciers were plentiful in the higher mountains, especially in those of the southwestern corner of Ireland, between Bantry Bay and the mouth of the

Shannon, and also in Bogeragh, Knockmealdown, and Comeragh Mountains.

NETHERLANDS

The number of the Scandinavian ice-sheets that invaded Holland is still unknown. Most writers, as Lorié (1913), Botke (1917), Tesch (1928), and Keilhack (1926, page 458), hold that only one ice-sheet did. The three writers first mentioned think that the ice-sheet corresponded to that of the third glacial epoch in the Alps, the Riss, but Keilhack correlates it with the second Alpine glaciation, the Mindel. Molengraaff and van der Gracht (1913, pages 86, 88), van Baren (1920), and Grahmann (1928, page 143), however, think that the ice-sheet corresponding to the second Alpine glaciation reached about equally far into Holland as its successor.

The exact outer border of the Riss ice, about whose invasion of the Netherlands all agree, is, however, not well known. It may have followed the Rhine; it may have run through Utrecht; or, most probably, it may have run through Amsterdam (see Molengraaff and van der Gracht, 1913, page 79). The discrepancy in the correlation of the most extensive ice-sheet in the British Isles with the second (or eventually the third) Alpine glaciation and in the correlation of the glacial drift in Holland with the third Alpine glacial epoch should be noted.

DENMARK

In Denmark three glaciations, corresponding to the last three of the four alpine glaciations, have been distinguished (Madsen, 1928, page 86). During the first two all of Denmark lay beneath ice, there being not even nunataks. The terminal moraines of the last Scandinavian ice-sheet run south of the Limfjorden from the coast of the North Sea to the center of Jylland, and thence nearly due south to the Kiel Canal, where they begin to curve (Madsen and Nordmann, 1928, plate 2; Jessen and Milthers, 1928, plate 1).

GERMANY

Only three Pleistocene glaciations are commonly distinguished in northern Germany. These three correspond to the last three in the Alps. They are called the Elster (Mindel), the Saale (Riss), and the Weichsel (Würm) (see, also, Grahmann, 1928, page 137). Four glaciations, however, have recently been held probable by Jaekel (1917), Range (1926), and van Werweke (1927), and the interglacial deposits, according to Milthers (1928*a*, page 326), appear to indicate three or four. The fourth glaciation, called the Elbe glaciation, is correlated with the first glaciation in the Alps, the Günz. Even a fifth glaciation may be represented by the Fläming (Warthe) moraines and drift, which

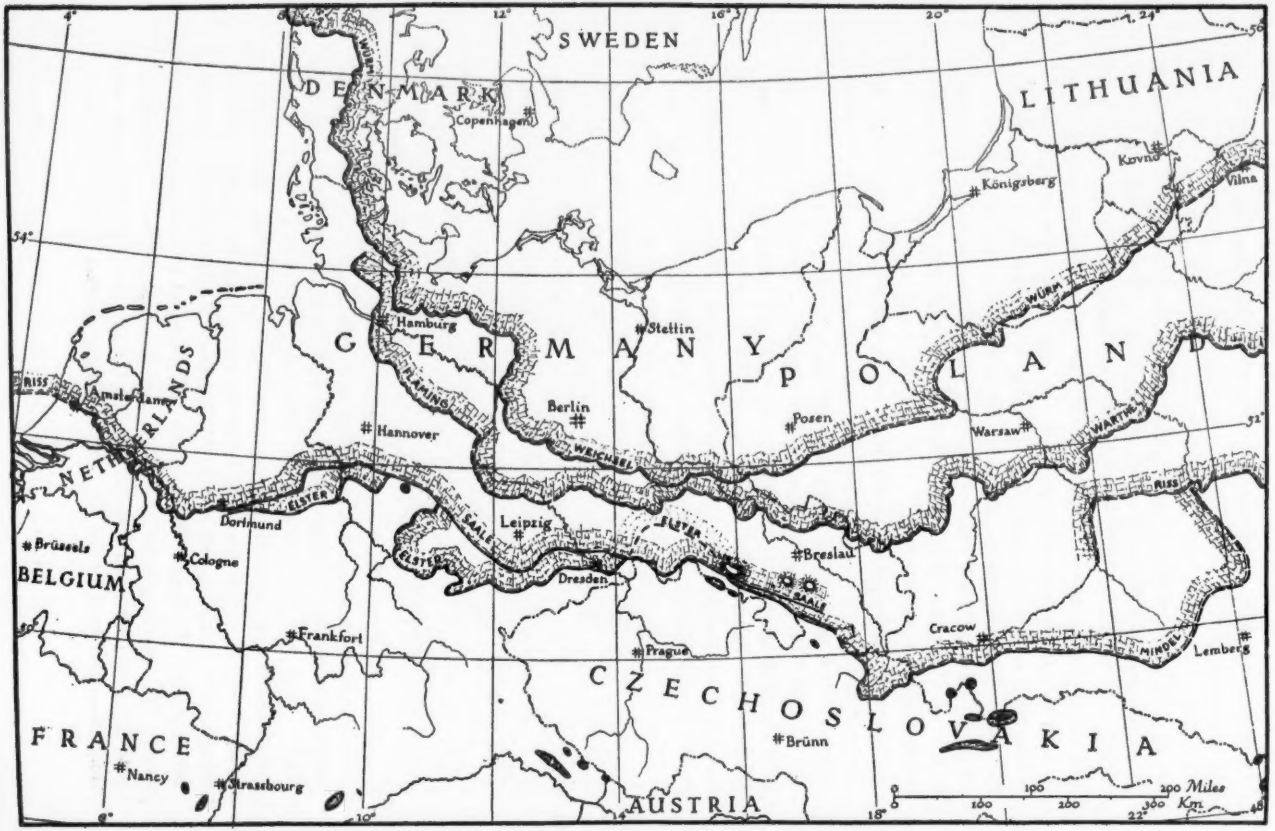

FIGURE 14.—*Drift Borders in Denmark, Holland, Germany, and Poland*
Elster = Mindel, Saale = Riss, Warthe (Fläming moraines), Weichsel (Brandenburg moraines) = Würm. Scale, 1 : 7.5 million.

are much younger than the Saale drift and considerably older than the Weichsel drift (Woldstedt, 1925*a*, pages 177, 180, 181). Woldstedt calls this glaciation the Warthe. Grahmann (1928, page 156), however, regards it as an early stage of the Würm glaciation. The whole list of possible glaciations in northern Germany and their probable correlatives in the Alps is thus: Elbe (Günz), Elster (Mindel), Saale (Riss), Warthe (no correlative in the Alps), and Weichsel (Würm). The unity of the Pleistocene glaciation in Germany, however, has advocates (Geinitz, 1903; Lepsius, 1910, page 524; Hucke, 1923). In his large treatise on the Quaternary Ice Age, that has appeared while this paper was in press, Woldstedt (1929, page 207) distinguishes the Elster, Saale, and Weichsel glaciations. The Fläming (Warthe) moraines are regarded as a stage of the Saale glaciation.

The extent of the Elbe glaciation is unknown. An attempt to map the borders of the Elster and the Saale glaciations has been made by Grahmann (1928), whom I have largely followed. A more conservative mapping has later been published by Woldstedt (1929, page 167).

The drift of the Elster glaciation appears first east of the Dutch boundary. Mostly it forms the outermost limit of the glaciated area. From a point south of Dortmund its border runs in a crooked line eastward to a point north of Harz, and thence southward in a big curve to Erfurt and Chemnitz. South of Dresden the border turns northeastward in the Neisse Valley to a point north of Görlitz, and thence finally southeastward, along the Sudetes.

The outer limit of the Saale glaciation seems to run through Amsterdam southeastward to a point south of Wesel; thence eastward through Dortmund to a point north of Harz, and so southeastward to a point south of Leipzig, and finally eastward through Dresden.

Within these borders in Silesia a few mountains towered above the ice, namely, Zobten, in latitude 50° 50′ north, longitude 16° 45′ east; Rummelsberg, in latitude 50° 45′ north, longitude 17° 5′ east, and scattered summits in the Katzbachgebirge, in latitude 50° 55′ north, longitude 16° east, and the Reichensteiner Mountains, in latitude 50° 20′ north, longitude 16° 50′ east (Limpricht, 1926).

The limit of the last glaciation has been much discussed by glacialists (Gripp, 1924; Woldstedt, 1925, 1927; Grahmann, 1928). All seem to agree that the choice is between the Brandenburg and the Fläming moraines. The Brandenburg moraine forms the southern limit of the lake region in northern Germany. The region outside this moraine but inside the Fläming is much smoother and its topography is very much older. An interglacial epoch, or at least a very long interstadial stage, must have intervened between the deposition of the drift sheets

Elster = Mindel, Saale = Riss, Warthe (Fläming moraines), Weichsel (Brandenburg moraine)

outside and inside the Brandenburg moraine. Gripp concludes that these drifts indicate two distinct glaciations, and that the limit of the last ice-sheet is marked by the Brandenburg moraine. Woldstedt was inclined to leave the question open, but now favors Gripp's view. Grahmann (1928, pages 137, 139, 156), on the other hand, regards the Fläming as an older member of the last glaciation, the Würm. The glaciation of the Fläming zone is known as the Warthe glaciation, and that of the Brandenburg moraine as the Weichsel glaciation (Woldstedt, 1927, page 117).

The borders of the later glaciations in Germany shown on our maps have been supplied by Woldstedt on a scale of 1 : 1.5 million. The limit of the Warthe glaciation is determined with certainty at only a few places. It seems to run from a point west of Hamburg southeastward to Dessau and thence eastward through Kottbus and Glozau, on the Oder. The outer limit of the last ice-sheet, the Weichsel, marked by the Brandenburg moraine, runs southward through central Schleswig-Holstein to Hamburg, where it turns due east. At Plau the morainic line runs southward and southeastward to Brandenburg, where it veers to the east-southeast, past Kottbus and Grünberg, to Lissa, just beyond the Polish boundary.

POLAND

In Poland, according to Limanowski (1922, page 366), whom other Polish geologists follow (Kulczýnski, 1923, page 181; Kozlowski, 1924, page 114), two glaciations, corresponding to the last two in the Alps, are recorded. Limanowski thinks that in northern Europe, as well as in the Alps, there were four Pleistocene glacial epochs, but that the successive ice-sheets did not cover the same areas. Instead, each successive ice-sheet outside of Scandinavia extended eastward beyond its predecessor. Thus, the first glaciation is believed to have comprised Norway and England; the second, Scandinavia, England, Holland, and Germany; the third, Scandinavia, England, Germany, Poland, and western Union of Soviet Socialist Republics; and the fourth, Scandinavia, Germany, Poland, and Union of Soviet Socialist Republics. Pawlowski (1928, page 19), however, finds no evidence for an eastward migration of the successive ice sheets.

The first glaciation in Poland, according to the Polish view, was the correlative of the third Alpine glaciation, the Riss, and was the most extensive, reaching south of Krakow and Przemysl (International Geological Map; Kozlowski, 1924). West of Lwow the extreme drift border turns northeastward and, after crossing the Bug River, follows the east side of this river to a point north of Chelm, where it disappears

under later drift. There is no drift east of this line, though drift is indicated on older maps (Wollosowicz, 1924, 1923).

The limit of the second Polish glaciation, correlated by Polish geologists with the fourth glaciation in the Alps, the Würm, is thought to be recorded by the central Polish terminal moraines (Kozlowski, 1924, page 115; Wollosowicz, 1924, 1928), which, as mapped by the Polish glacialists, cross the country in a gentle curve from west to east, running from Lissa, just north of Lublin, Chelm, and Kovel, until they strike the Goryn River (26° 30′ east), which they follow northeastward to the Pripet River. For reasons that will presently be given, only the part east of Lublin has been shown on the maps. Pawlowski (1928, page 19) thinks, however, that the two glaciations distinguished in Poland are not proven to correspond to the two last ones in the Alps.

These views of the Polish glacialists do not agree with those now held by German and Russian geologists regarding the regions immediately west and east. An outsider should not, perhaps, attempt to decide what view is right, but it is here necessary to make some decision, for all the divergent views can not be expressed on the map. The Poles distinguish but two Pleistocene glaciations; most of the Germans and Russians distinguish three. The peripheral drift in western Poland is referred to the Riss and that in eastern Poland is referred to the Würm, but the drift on the German side of the frontier is assigned to the Mindel (Elster) and that in Union of Soviet Socialist Republics to the Riss. However, in view of the difficulty the Germans have in determining whether the Fläming (Warthe) moraine forms the limit of the last glaciation or not, the difference of opinion between Polish and German geologists is considerably reduced.

The border of the second drift of the Polish geologists, the Würm, probably connects with the extreme drift in Union of Soviet Socialist Republics, though there now is a small gap in the mapping.

The Fläming (Warthe) moraine, which crosses at an acute angle the moraine of the second glaciation of the Polish geologists south of Lods, is here shown in accordance with Woldstedt's latest view (1920, page 217, and personal letter in 1928). It runs from Glogau, on the Oder, east-southeastward to the sharp loop of the Varta River, and thence east-northeastward, past the junction of the Vistula and Piliza rivers, to Lukuv and Bielsk.

The German, Russian, and Finnish geologists agree that the southern limit of the lake region on the European continent probably forms the southern border of the last ice-sheet, the Weichsel. This border as far east as 23 degrees is shown on the present maps in accordance with Woldstedt's latest mapping and combination. The boundary follows

in part and connects what Polish geologists regard as three separate lines of stadial moraines (Kozlowski, 1924). From Lissa, on the German frontier, it runs east-northeastward to Plock, on the Vistula. After curving northward it continues east-northeastward along the frontier between East Prussia and Poland to Augustow and Vilna, where it turns toward the southeast (see Kozlowski, 1924, page 115).

UNION OF SOVIET SOCIALIST REPUBLICS

The number of Quaternary glaciations recorded in Union of Soviet Socialist Republics ranges from two to four. Besides, two Pliocene ones are distinguished by Pavloy (1925). The Pleistocene glaciations are correlated with the Mindel, Riss, and Würm. Two separate Pleistocene glaciations are recognized in central Union of Soviet Socialist Republics by Girmounski (1925); in southern Union of Soviet Socialist Republics by Sobolev (1925); in western Union of Soviet Socialist Republics by Sawicki (1926–27); in the east Balticum by Hausen (1921, page 31), Mortensen (1926, page 15), and Kraus (1928, page 18); and in northeastern Union of Soviet Socialist Republics by Grigoriev (1924). Girmounski correlates these glaciations with the Mindel and Riss, and Sawicki correlates them with the Riss and Würm. Evidences of three glacial epochs are found by Florov (1926), Girmounski (1927), and Mirčink (1927, 1928). These glaciations are correlated with the Mindel, Riss, and Würm. Mirčink (1928, page 689) deduces his three glaciations from the stratigraphy of the glacial deposits, from the stratigraphy of the loess, and the history of the Caspian Sea, which has had three high-water stages. Finally, four glacial epochs are found by Krokos (1927, page 2; 1927*a*), deduced from as many loess horizons, separated by three fossil soils of chernozem type.

No attempts have been made to map four glaciations in Union of Soviet Socialist Republics, three being the greatest number whose borders have been outlined. The extreme limit of drift shown on our maps accords with the geological map of Union of Soviet Socialist Republics of 1915, which in its delineation of the drift border differs only in minor details from the International Geological Map. The border is called the "limit of erratic blocks" and is probably rather approximate. The drift limit in the Dnieper Valley accords with that given by Dmytrijev (1928), who states that the task of fixing accurately the outermost ice border is difficult, because at many places the till is concealed by younger sediments. The extreme limit of the drift shown on the International Geological Map for eastern Poland is incorrect, for there are no glacial deposits southeast of Chelm. The outer drift in eastern Poland, as mapped by Wollosowicz (1924), probably connects with the

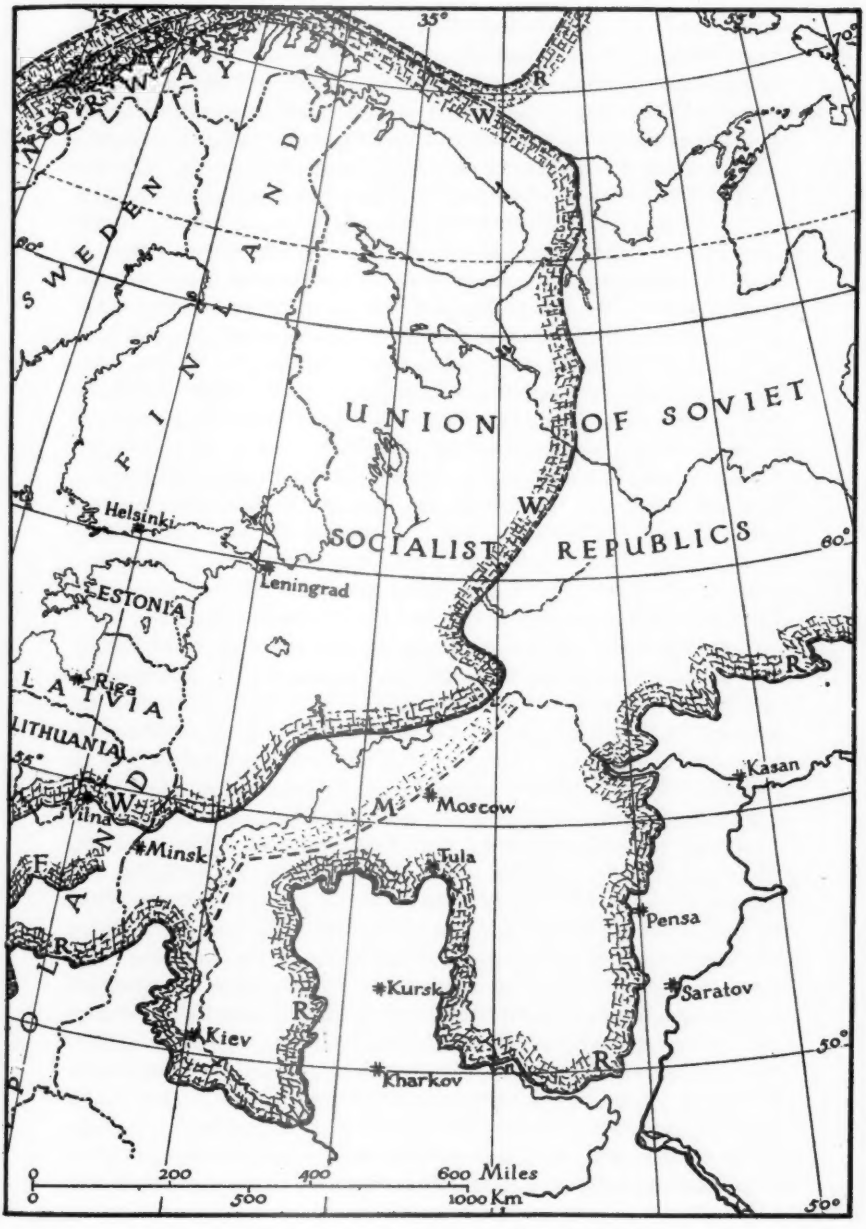

FIGURE 15.—*Drift Borders in Union of Soviet Socialist Republics and Poland*

M, R, F, and W designate Mindel, Riss, Fläming, and Würm respectively. Equal area projection. Scale, 1 : 15 million.

extreme drift in the adjacent Union of Soviet Socialist Republics, though there is a small gap in the mapping. The outermost drift border can be described briefly as running east-northeastward from a point in latitude 51° 20′ north, longitude 26° east, to another point in latitude 61° north, longitude 59° east, in the Ural Mountains, with two enormous lobes reaching far southward in the Dnieper and the Don-Worona valleys. In Siberia the boundary probably runs southeastward to a point in latitude 59° 15′ north, longitude 64° east, and thence northeastward, in a practically straight line, across the Obi and Yenisei rivers to Khatanga Bay, in the southeastern part of the Taimyr Peninsula (Obruchev, 1926, plate 10). Ice that spread from a center in the northern Urals perhaps covered the land northwest of the line indicated, but probably did not extend out into the sea.

The peripheral drift is dated as Mindel by Pavlov (1925), as Riss by Krokos (1927, page 3) and Mirčink (1928), and as Würm by Kulczyński (1923, page 184) and Florov (1927, page 193).

According to Mirčink (1928), the probable limit of the Mindel icesheet lies inside this drift border and runs in a crooked line from the Goryn River in latitude 52° north, longitude 27° east, over Mozir, Mohliev, Moscow, and Narechta to the Volga, in latitude 57° 30′ north, longitude 41° east. The Mindel drift being older than and covered by the Riss, its course as shown may be at best approximate.

In the Union of Soviet Socialist Republics, as in Germany and Poland, the boundary of the last glaciation may coincide with the southern limit of the lake-studded morainic region. The general trend of the boundary of glaciation has long been known, but in the delineation of its details many important changes have been made and others will no doubt be made in the future. From Vilna the youngest drift border may run southeastward to a point north of Minsk (Missuna, 1902; Wollosowicz, 1923, page 86; Kozlowzki, 1924, page 115); thence northeastward for a short distance, and next eastward and northeastward to a point in latitude 56° 45′ north, longitude 33° east (Hausen, 1912; Kraus, 1928; Mirčink, 1928). According to Missuna (1909), its course continued unchanged to Vesiegonsk, on the Tichvina River, in latitude 58° 30′ north, longitude 37° east, but according to Mirčink's new map it should trend nearly eastward to Jaroslav, on the Volga. Beginning at Jaroslav the border may make an S-curve, and then from a point in latitude 59° north, longitude 39° east, may run northeastward to Osseredok, on the Dvina. From Osseredok the border of the youngest drift probably continues due north to and across the Gulf of Mezen to Kanin Peninsula, whose southwestern part and western coastal rim contain drift from Kola (Ramsay, 1900, page 116; 1904, pages 31, 45). On a small map

published since our maps were drafted, Bobnovo (in Žirmunskij, 1929, page 25) marks the Brandenburg (Weichsel)-Vyshiy Volochok stage somewhat differently, and extends the Fläming (Warthe) moraines in a fairly smooth curve over Moscow beyond the Volga—that is approximately where the eastern part of the Mindel drift border is shown on our map.

ENGLAND, NETHERLANDS, GERMANY, POLAND, AND UNION OF SOVIET SOCIALIST REPUBLICS

The divergent results reached by glaciologists in different countries seem to justify a brief comparative treatment of the number, extent, and age of the north European drift sheets. In Ireland two drift sheets, correlated with the second and the fourth Alpine glaciations, have been differentiated. The older drift covers the entire island; the newer covers the northern part of it. In England there seem to be three drift sheets, corresponding to the Günz, Mindel or Riss, and Würm glaciations. The oldest sheet seems to be of totally unknown extent, the middle sheet may reach down to the Thames Valley and the Bristol Channel, and the youngest may extend south of the Wash, to Leeds, and the Bristol Channel.

Turning to the continent, we find that one or two glaciations are recognized in the Netherlands and correlated with the second and the third stages in the Alps.

Again, in Germany three or more glaciations are recognized, the three generally accepted being the Elster, Saale, and Weichsel, contemporaneous with the Mindel, Riss, and Würm. The two first named reached below the fifty-second parallel of latitude in the western part of the country.

If there really was but one glaciation in Holland, there was also only one in westernmost Germany; and if there were two in western Germany, there were two in Holland. Although nothing is known about the extent of the earliest English glaciation, it is perhaps permissible to correlate the two old glaciations in England with the two old glaciations in Germany and to infer two glaciations in Holland. If this inference is justified, the problem of the age of the glaciations should be considered. As the Dutch and the German geologists recognize a glaciation of Riss age, the middle drift (Purple Clay) in England should perhaps also be correlated with the Riss, which is one of Kendall's alternatives. To say that the oldest English drift is Günz and the oldest well-known German drift is Mindel probably means that one of the datings is wrong.

The southern boundaries of the two old German drift sheets cross the country between the fifty-second and fiftieth degrees of latitude in a

direction somewhat south of east, but the boundary of the last ice-sheet makes a curve from central Schleswig and from Hamburg down to the fifty-second parallel and eastward to Lissa.

The Polish geologists differentiate two glaciations, which they correlate with the Riss and the Würm. They assign to the Riss the drift boundary that extends from the German frontier past Krakow and Przemysl northward to Chelm, and the surface drift north of a line from Lissa past Lublin to Goryn River, southeast of Pinsk, to the Würm.

The Russian geologists hold divergent views. Florov (1927, page 193) agrees with the Polish glacialists that the Würm glaciation in eastern Europe was more extensive than any of its predecessors—that is, that it reached far down into southern Union of Soviet Socialist Republics. Pavlov (1925) and Krokos (1927, page 3), however, hold that it was the Mindel ice-sheet that attained this southern position, and Mirčink (1928) thinks it was the Riss. The view that the Würm glaciation was most extensive seems to be inadequately sustained. In Germany the outer limit of the topographically young lake region is regarded also as the limit of the last ice-sheet. This lake region continues northeastward through northern Poland, east Balticum, and the northwestern Union of Soviet Socialist Republics to the mouth of the White Sea, and it may here, if in Germany, mark the extreme limit of the last glaciation. If, on the other hand, the last ice had reached as far south in Union of Soviet Socialist Republics as the drift, the accepted border in Germany would be wrong. However, uncovered peat bogs from the last interglacial epoch are found a little outside the accepted border, some 35 miles (60 kilometers) southeast of Hamburg (Jessen and Milthers, 1928, page 312).

Which one of the older glaciations, the Mindel or the Riss, laid down the outermost drift in Poland and Union of Soviet Socialist Republics? As the drift border that extends eastward from Chelm, in Poland, can not very well be Würm, it may be the Riss. The older drift border which runs through Chelm, Przemysl, and Krakow, may then be Mindel, a conclusion that agrees best with the determination reached for Germany by Grahmann (1928, page 143). As the probable Riss moraines east of Chelm and the Bug River form the outermost drift, they perhaps connect with the outermost drift border in Union of Soviet Socialist Republics, which, according to Mirčink, is of Riss age.

BARENTS SEA

If the extreme southern boundary of the unglaciated area is only approximately known, it is but natural that the northern limit is not well mapped. From the ice center in the northern Urals and the

Timan Mountains the ice spread chiefly east, north, and west. In northwestern Siberia the ice perhaps confined itself to the land (Obruchev, 1926, plate 10). The northwestward push of the ice was strong, for boulders from the Urals and the Timans are found as far west as the Kanin Peninsula and fossils in blocks on Kolgujev are identical with fossils found in the Timan Mountains (Ramsay, 1904, pages 32, 38; 1912). The ice moving northward from this center may therefore have coalesced with the ice-cap centering on Novaya Zemlya.

Nearly all the north half of Novaya Zemlya is covered by a continuous ice-cap (Grönlie, 1924, plate 30). Between this ice-cap and the strait called the Matochkin Shar there are valley glaciers and on both sides of that strait are cirque glaciers. During Pleistocene time the entire Novaya Zemlya, except, perhaps, the highest mountain summits near the Matochkin Shar, may have lain beneath ice (Grönlie, 1924, page 87). The ice-sheet must have reached a height of 1,100 to 1,200 meters (3,350 to 3,660 feet) above the present sea level and must have extended far beyond the present coast into the shallow surrounding sea. Separate drift sheets have not yet been distinguished.

Kolguev Island may at the same time have been reached by ice from the Timan Mountains. No outcrop of rock has yet been observed on this island, which seems to be built up exclusively of glacial and postglacial deposits of till and marine sediments (Feilden, 1896; Tolmachev, 1927, page 70). Whether the island was covered with ice during all the glacial epochs is not known.

The Kanin Peninsula, Kola, and Fisher Peninsula, in latitude 70° north, longitude 32° east, may have been entirely covered with ice when the glacier reached its maximum extent (Ramsay, 1900, page 111). The last Scandinavian ice-sheet reached over the western part of the Kanin Peninsula and it may have extended a short distance out into the shallow Barents Sea, off Kola.

It is not certainly known whether the Barents Sea, which near the continent and islands is less than 200 meters (610 feet) deep and in its central parts is almost everywhere less than 400 meters deep, was filled with ice from the surrounding lands or even formed a center of ice outflow. Tanner (1915, pages 137, 698) points out that the pressure of a large mass of ice in the Barents Sea would account for the westerly position of the ice shed in northern Fenno-Scandia, but at the same time he stresses the poverty of the evidence for the existence of this ice. Grönlie (1924, page 87) believes that ice masses from the surrounding lands and islands left little open ice-free water in the shallow sea. The occurrence in the Kanin Peninsula of boulders that may have been transported by ice from Novaya Zemlya (Ramsay, 1904, page 36) suggests the presence

of ice in that sea. On the other hand, the absence of foreign ice-borne material on Bear Island and the fact that this small island formed a local center of glaciation sets a certain limit to the extent and thickness of the possible ice. So, also, does the fact that King Charles Land was not overrun by ice, which also contravenes De Geer's view that the Spitsbergen ice centered on the continental shelf east of Spitsbergen in Pleistocene time. In view of the relatively small area of the surrounding islands and the power of the sea to break up glacier ice, it therefore seems probable that glacier ice occupied only the southeastern part of the Barents Sea—that is, the part lying near the continent between Kola, Union of Soviet Socialist Republics, and Novaya Zemlya, as well as the fjords and shallow waters bordering Spitsbergen, Franz Josef Land, and other islands. On the other hand, the greater Barents Sea was probably filled with Arctic Pack and pack ice. At the end of summer the southern front of pack ice now lies along a line running from South Cape of Spitsbergen to the north end of Novaya Zemlya; at other times its lies farther south.

Pleistocene Glaciations in the Mountains of Europe

General statement

The study of present and past glaciations was started in the Alps, and, next to northern Europe and North America, the Alps are still the principal field of glaciological investigations. The study of the phenomena of the Quaternary ice age was early extended to other mountain ranges in central and southern Europe. So a voluminous literature on the subject has accumulated.

As known, the Pleistocene glaciations in the Alps were mapped in considerable detail by Penck and Brückner (1901–1909). Later the glaciations in Switzerland and in the eastern Alps were presented in still greater detail by Heim (1921, page 214), by Beck (1926), and by Krebs (1928, page 63). The former glaciation in Spain has also been studied by Obermaier (1921); and the traces of glacial action in certain areas in other parts of the continent have been clearly mapped. Too frequently, however, mapping has been replaced by lengthy descriptions, and little work in compiling maps has been done.

While the Pleistocene Ice Age in Europe has been generally divided into four glacial epochs, determined by phenomena observed in the Alps, little ground for such a division has yet been discovered in other European mountain ranges. In three of the Iberian Mountains—the Picos de Europa, the Sierra de Guaderrama, and the Sierra da Estrella—traces of two glaciations, the Würm and an older one, have been observed (Obermaier, 1921, page 161). Although direct evidence

of only one Pleistocene glaciation was found in the Pyrenees by Penck (1884, page 209), morainic lines there of apparently different ages suggest two. In Corsica as many as four glacial epochs have been differentiated by Lucerna (1910, page 91). The Würm glaciers are indicated by terminal moraines, the Riss glaciers mostly by lateral moraines, and the Mindel and Günz glaciers by ice-carved valleys and drift. Most of the formerly glaciated mountains in south-central France show evidence of three glacial epochs, the first of which is referred to the Pliocene by Boule (1921, page 36).

In Schwarzwald, southwestern Germany, the same four glacial epochs that are discriminated in the Alps may be recorded (Wepfer, 1924). In Böhmer Wald, on the boundary between Germany and Czechoslovakia, Pleistocene glaciers formed twice (Machatschek, 1927, page 33). In the Liptauer Alps, in latitude 49° 15′ north, longitude 19° 40′ east, four glacial epochs have been distinguished (Lucerna, 1908; Machatschek, 1927, page 374). In the High Tatra, in latitude 49° 15′ north, longitude 20° east, there are at a few places older moraines that lie somewhat outside of the Würm moraines, and in one region there are three beds of drift—facts that suggest two or three glacial stages (Partsch, 1923, page 168). Suggestions of two glaciations are found in the Transylvanian Alps of Rumania (de Martonne, 1900, p. 316); on Rila Mountain, in Bulgaria, in latitude 42° 15′ north, longitude 23° 20′ east (Cvijić, 1908); on Jakupica Mountain, in Yugoslavia, in latitude 41° 45′ north, longitude 21° 20′ east (Jovanović, 1928); and in mountains in Albania and Greece (Maull, 1921, page 119). In the Caucasus there is evidence of three distinct glaciations, which are correlated with the Mindel, Riss, and Würm and there are traces of a fourth (von Reinhard, 1929).

Outside the Alps the extent of the glaciers during the different glaciations has been shown on but few maps and the details involve areas too small to be shown on our maps. When evidence of only one glaciation is on record, the glacial epoch in which it occurred is not known. For many areas our present knowledge permits us to map only the Pleistocene glaciers, without distinction of epochs of glaciation.

The supposed glacial phenomena in the Ardennes of southeastern Belgium are now attributed to solifluction or other action, not to the action of ice (Lorié, 1924). Supposed moraines and glacial potholes in the Pfälzer Wald, in western Germany, in latitude 49° 20′ north, longitude 8° east, are now generally ascribed to other causes than ice (Rüger, 1925). So also are certain formations in Rhön, in latitude 50° 30′ north, longitude 10° east, that were formerly described as moraines (Dietrich, 1911), as well as in the Thüringer Wald, in latitude 50° 40′

north, longitude 10° 40′ east (von Zahn, 1918), and also supposed traces of glacial action in the Frankenwald, in latitude 50° 20′ north, longitude 11° 30′ east (von Zahn, 1918), and in the Erzgebirge, in latitude 50° 30′ north, longitude 13° east (Rathsburg, 1928). Whether depressions on Mount Etna, Sicily, are Pleistocene cirques or not seems to be doubtful (Maier, 1929; Leyden, 1929).

FRANCE AND IBERIAN PENINSULA

In France outside of the Alps and the Jura, there were many glaciers in Pleistocene time in the Vosges Mountains, in latitude 48° to 49° north, longitude 7° east (Schumacher, 1908; Meyer, 1911–1913; Jessen, 1920; Nordon, 1928, page 543), and on the south-central plateau, in latitude 44° to 46° north, longitude 1° to 4° east (Boule, 1896, 1902; Arbos, 1922, 1927; Baulig, 1928, page 33). Glaciers were formed on this plateau in the Monts du Forez, Montagne de la Margeride, Montagne de la Lozère, Montagne d'Aubrac, Cantal, Mont Doré, and Monts du Limousin.

In the Pyrenees a network of glaciers extended far down the slopes from longitude 40′ west to longitude 2° 30′ east (Penck, 1884; Nussbaum, 1928). Many of the high ranges in the northwestern part of the Iberian Peninsula, as well as the Sierra Nevada, supported Pleistocene glaciers (Obermaier, 1921). Central Corsica was heavily glaciated (Lucerna, 1910).

ITALY

The Italian Peninsula shows traces of Pleistocene glaciers from the arch of the boot up to Florence. In southern Italy, about in latitude 40° north, longitude 16° east, glacial traces are reported from the Pollino, Sirino, Cervati, and Volturino Mountains (Crema, 1923; De Lorenzo and Dainello, 1923; Biasutti, 1923). In the region between Rome and the Adriatic Sea, Pleistocene glaciers existed in the Simbruini, Marsicani, Majella, Fucino, Ocre, and Gran Sasso Mountains (Franchi, 1919; Almagià, 1919; Sacco, 1908; Crema, 1919, 1919*a*, 1919*b*). Glaciers also occurred along the upper Arno due east of Florence (Crema, 1919*b*).

THE ALPS

Although the Pleistocene glaciations in the Alps were insignificant in comparison with those in northern Europe and in North America, the classification of the Alpine deposits as worked out by Penck and Brückner (1901–1909) has won more general recognition than any other. The glaciations distinguished are called the Günz, Mindel, Riss, and Würm.

The extent of the oldest glaciation is not known. The Mindel and Riss seem to have covered largely the same areas, and certain mapping

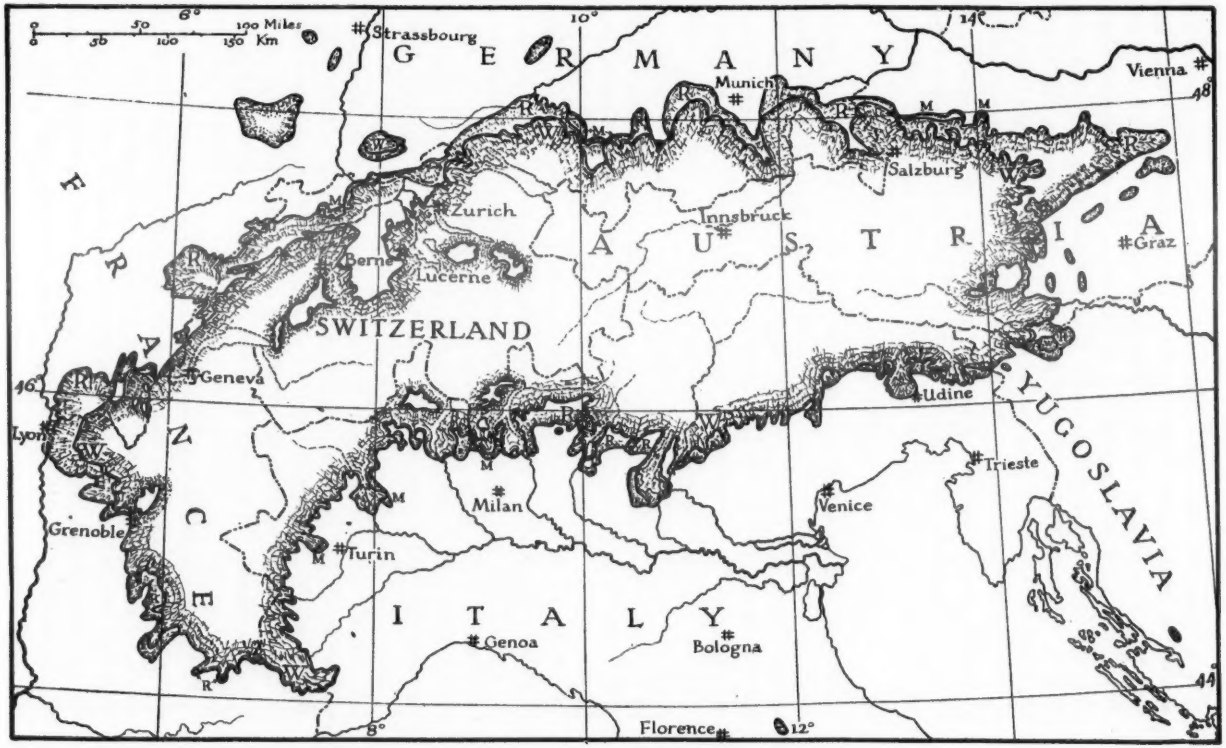

FIGURE 16.—*Pleistocene Glaciations in the Alps*
M, R, and W designate the Mindel, Riss, and Würm glaciations. Scale, 1 : 5 million.

of their borders is therefore difficult. Along the northeastern boundary of the glaciated region Mindel moraines were indicated by Penck and Brückner just outside the Riss Moraines, but Krebs (1928) does not distinguish between them on his recent map. In the north-western part of the ice-covered region the Riss glaciation forms the extreme border. On the Italian side Mindel and Riss deposits are locally identified outside the Würm moraines, most of which form the boundary to the unglaciated region. In the high ranges there were nunataks. Our maps for the eastern Alps (east of longitude 9° east) essentially follow Krebs (1928, page 63), and those for the western Alps follow Penck and Brückner (1901–1909), Heim (1921, page 214), and Beck (1926).

GERMANY, CZECHOSLOVAKIA, POLAND, AND RUMANIA

Between the Alpine ice-cap and the Scandinavian ice-sheet glaciers were formed in many mountains. In southern Schwarzwald, in the bend of the Rhine, in latitude 47° 45′ north, longitude 8° east, numerous glaciers were formed, although part of the supposed evidence of their existence has been found to be invalid (Klute, 1911; Brückner, 1918; Wepfer, 1924; Schrepfer, 1926; Krebs and Schrepfer, 1927; Buri, 1928). Evidence of former glaciation is seen on the Rauhe Alb, in latitude 48° 30′ north, longitude 9° 30′ east (Freudenberg, 1920), and in the Bayrischer Wald, in latitude 49° north, longitude 12° 45′ east (Priehauser, 1927). In the Böhmer Wald, in latitude 49° north, longitude 13° 30′ east, eleven Pleistocene glaciers are recorded by striæ, lakes, and other phenomena. Some of these are found on the mountain peaks Arber and Rachel. All the glaciers existed during the Würm epoch (Rathsburg, 1928, page 158). Some glacial phenomena are also found in the Harz, in latitude 51° 45′ north, longitude 10° 30′ east, which was surrounded on three sides by the most extensive ice-sheet (Kayser, 1881).

In the Riesengebirge, in latitude 50° 45′ north, longitude 15° 30′ east, just outside the southern limit of Nordic drift, there were Pleistocene glaciers on Hohes Rad and Schneekoppe (Worms, 1927; Machatschek, 1927, page 289). Glaciers also formed on Krkonoši, immediately south of these mountains (Vitásek, 1926), and in the Altvatergebirge, in the southern Sudetes, in latitude 50° north, longitude 17° 15′ east (Lucerna, 1924).

Farther southeast, in the border regions of Poland and Czechoslovakia, evidence of glacial action has been seen on Pilsho, in latitude 49° 30′ north, longitude 19° 20′ east, and Babia Gora, in latitude 49° 35′ north, longitude 19° 40′ east (Sawicki, 1913); in the Liptauer Alps, in latitude 49° 15′ north, longitude 19° 40′ east (Lucerna, 1908); in the High Tatra, in latitude 49° 15′ north, longitude 20° east (Partsch, 1923); and in the

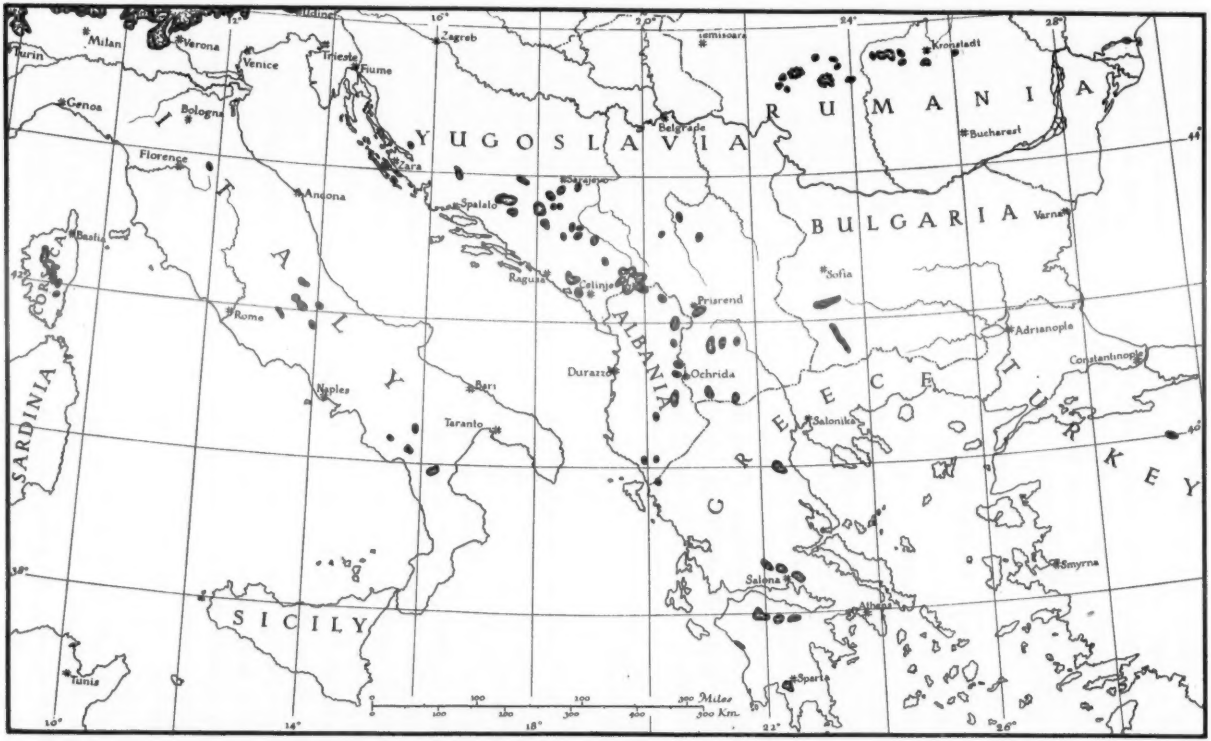

FIGURE 17.—*Pleistocene Mountain Glaciation in Italy and the Balkan Peninsula.* Scale, 1 : 10 million.

Nizna Tatra, in latitude 49° north, longitude 19° 30′ east (Vitásek, 1926). Still farther southeast, where Poland, Czechoslovakia, and Rumania join, several small valley glaciers were formed in Pleistocene time (Romer, 1906; Pawlowski, 1917, 1925; Vitásek, 1926*a*). In mountainous northwestern Rumania and in the Transylvanian Alps glaciers were rather numerous (de Martonne, 1900; Székány, 1917).

BALKAN PENINSULA

In Pleistocene time glaciers were formed on a large number of mountains in the Balkan Peninsula, from the Save and Danube down to southernmost Greece, as revealed especially by Cvijić's tireless studies and by explorations made by German geologists during the World War. The glaciers were particularly numerous on the mountain ranges that parallel the Adriatic Sea. The former glaciation in Yugoslavia has been treated by Stroh, Grund, von Sawicki, Schubert, Dedijer, Gripp, Kossmat, von Telegd, Jovanovoć, and Milojević, and above all by Cvijić. Our knowledge of the glaciation in Albania is due to Novack (1920, page 115) and Louis; of that in Greece to Maull; and of that in Bulgaria to Cvijić (1908) and Penck (1925). The Pleistocene mountain glaciation in Albania was more widespread than our maps show (Novack, 1929, page 125).

UNION OF SOVIET SOCIALIST REPUBLICS

The Caucasus Mountains have a ragged band of snowfields and glaciers along their crests in their western part, from latitude 41 degrees to 46 degrees east. During Pleistocene time there was a network of glaciers and large icefields in the western part of these mountains, but only separate glaciers in the eastern part (von Reinhard, 1914, 1927; Renngarten, 1925; Kusnezov, 1926). Three distinct glaciations, correlated with the Mindel, Riss, and Würm in the Alps, are clearly recorded in the Caucasus, and there are traces of a fourth, an older glaciation (von Reinhard, 1925, page 98; 1927; 1929), but the outline of the glaciated areas is mapped only approximately.

In the Ural Mountains, south of the boundary of the largest ice-sheet, there were probably local glaciers. Glaciers also occurred perhaps during other less widespread glaciations, as is suggested by the occurrence of drift in the region west of Ekaterinburg, in latitude 57° north, longitude 60° 20′ east, some 275 miles (450 kilometers) outside the southernmost ice-front (Poliakoff, 1877). Local glaciers may have been formed in the northern Urals and the Timan Mountains during the last glaciation, when the Scandinavian ice reached only to longitude 44 degrees east. At present there are no glaciers in the Urals.

Pleistocene Glaciations on Islands in Arctic and Subarctic Europe

FRANZ JOSEF LAND

The numerous islands known as Franz Josef Land are now almost entirely covered with ice, which at many places ends in high cliffs at the sea (Ziegler Polar Expedition, 1907, Maps B and C; also Koettlitz, 1898, page 641). The ice is not thick and the sea is less than 200 meters (610 feet) deep. During the Pleistocene epoch the extent of the ice was greater than it is now (Wiese, 1928).

KING CHARLES LAND

The small islands that lie between latitude 78° 40′ and 79° north and longitude 26° and 30° east, east of Spitsbergen, now contain only one glacier, which is on Svenska Förlandet. During the Pleistocene epoch they probably supported several glaciers, but they may not have been overrun by a continuous ice-sheet from Spitsbergen or from the Barents Sea. No striated ledges have been observed, but glaciated boulders and till are found (Nathorst, 1901, pages 366-373; 1910, page 414).

SPITSBERGEN

Ice now covers the greater portion of Spitsbergen, leaving free only crests and summits of mountains, a rim along the coasts, and some low outlying regions. Till, erratics, striæ, and roches moutonnées, even on peripheral islands, suggest that ice covered and filled highlands, lowlands, and fjords and extended out on the continental shelf, where it was depleted by detachment of icebergs and by melting. Only the highest summits may have risen through the continuous ice-cover (De Geer, 1900; 1913, pages 274-277; Nathorst, 1910; B. Högbom, 1911, page 55; von Drygalski, 1911, pages 45, 52; O. Nordenskjöld, 1921, page 18; 1926, page 24).

Roches moutonnées on islands in Hinlopen Strait, in northeastern Spitsbergen, and erratics, striæ, and roches moutonnées in southeastern Spitsbergen suggested to De Geer (1900, page 431; 1913, page 276) a general westward flow from an ice center in the shallow sea somewhere east of Spitsbergen. King Charles Land, however, which stands in the supposed center of the glacier, appears not to have been overrun by ice (Nathorst, 1910, page 414). Records of only one extensive glaciation have been obtained (von Drygalski, 1911, page 46).

BEAR ISLAND

Bear Island, which lies halfway between Norway and Spitsbergen, now has no permanent snowdrifts. During the Pleistocene epoch all of it except the high cone-shaped summits of Mount Misery may have

been covered by a local ice-cap that radiated from the center of the island (Nathorst, 1910, page 291; Horn and Orvin, 1928, pages 44, 50). Only one glaciation is indicated and, as its traces include striæ, it may have been the last glaciation. No material that suggests invasion of ice from the Barents Sea has been found.

JAN MAYEN

In Jan Mayen, a lonely volcanic island in the arctic Atlantic, in latitude 71° north, longitude 8° 30′ west, several glaciers are borne on Mount Beerenberg (Mecking, 1925, page 116). Ice fills the main crater and envelops the upper slopes, from which glaciers radiate toward or reach the sea. The entire island was probably covered with ice in Pleistocene time.

ICELAND

There are about fifteen ice-caps and glaciers in Iceland, most of them in its south-central part. The Vatna Jökull is the largest glacier in Europe. The Pleistocene glaciation was much more extensive. Two stages are indicated by two drift sheets, which are separated by an erosion level on the high plateau (von Knebel, 1905, 1906; Reck, 1926). During each period ice probably covered all of Iceland, radiating in all directions from its central part (Reck, 1911, page 268).

FAROE ISLANDS

During the Pleistocene epoch the Faroes were glaciated (Geikie, 1895, page 597; Grossman and Lomas, 1895; Böggild, 1928). The ice reached a height of about 500 meters (1,600 feet) on the northern islands, filled lowlands, fjords, and sounds and flowed in all directions into the sea, where it discharged icebergs. Only the highest summits rose above the ice.

Pleistocene Glaciations in Asia

The Pleistocene glaciation in Asia was small in comparison with that in Europe and North America, because of the enormous size of the continent and the consequent great distance of the interior from the ocean, because of precipitation of the moisture of the summer monsoon in the high mountain ranges to the south, and because of great evaporation. There was no great ice-sheet, but there were rather large ice-covered areas, not only in the mountains, but on the northern plains. Ice stood on the Pamir Plateau and in northwestern Siberia. The actual extent of most of the former glaciers is not exactly known and they have been mapped only for a few regions. The maps here given partly represent generalizations made from descriptions and statements based on scanty observations. They have been compiled from maps given by

Geikie (1895, page 691), Obruchev (1926, plate 10), and Berkey and Morris (1927, page 383), as well as from descriptions and narratives.

The number of Quaternary glaciations distinguished in different parts of Asia ranges from one to four. As this subject has recently been treated (Antevs, 1928, pages 4–8), only the results of the latest studies will be considered here. Edelstein (1926) finds evidence of only one glaciation on the west Siberian plain, though he believes there may have been an older glaciation. Von Reinhard (1928) recognizes only one epoch of extensive glaciation in the East Sayansk Mountains. Schultz (1916, page 206) and Prinz (1927, page 323) observed traces of two glacial stages in Pamir and adjacent regions. According to Schultz, the last glaciation was the most widespread. Evidences of three separate epochs of glaciation on the Lena-Aldan Plateau were discovered by Gregoriev (1926, page 200). The largest glaciers appeared to have belonged to the second glaciation. Schultz (1928) mentions three glaciations in the Altai, where Fickeler (1925) recognized with certainty only one. The extent of the different glaciations has been mapped by some glaciologists, but our general maps show only the greatest extent of the ice irrespective of age.

Northwestern Siberia seems to have been buried by ice that spread from the northern Ural Mountains. This ice was a part of the north European ice-sheet. Even in Taimyr Peninsula the ice moved from the southwest toward the northeast (Sverdrup, 1922, page 16). The evidence includes drumlins and erratics, but not striæ. The islands in the Arctic Ocean off Siberia were covered by ice. In northeastern Siberia, east of the Lena River, all the high mountain ranges carried large glaciers. The fjords on the Siberian coast of Bering Sea indicate the existence of local glaciers (A. Nordenskiöld, 1882, pages 569, 583–585). The mountains of Kamchatka supported a network of glaciers. In the Hida Mountains, in Japan, there were small hanging glaciers. The Sikhota Alin, on the Siberian east coast, and the Shan Alin, in Korea, seem to have borne glaciers (Geikie, 1895, page 691; Berkey and Morris, 1927, page 383). So did the Suma Hada Range, northwest of Peiping (Przewaljski in Nathorst, 1883, page 149). On Wutai-shan, in latitude 38° 45′ north, longitude 113° 15′ east, and Taipai-shan, in latitude 34° 20′ north, longitude 107° 30′ east, there are small cirques (Schmitthenner, 1923, page 146; Olbricht, 1923, page 727).

In southwestern China, at about latitude 30° to 32′ north and longitude 103° 30′ to 104° east, there are cirques, till, and small modern glaciers (von Richthofen, 1882, page 641; 1912, pages 66, 307). The mountains just to the southwest also present traces of more vigorous former glaciation (Ward, 1924; Gregory, 1924; Handel-Mazzetti, 1927).

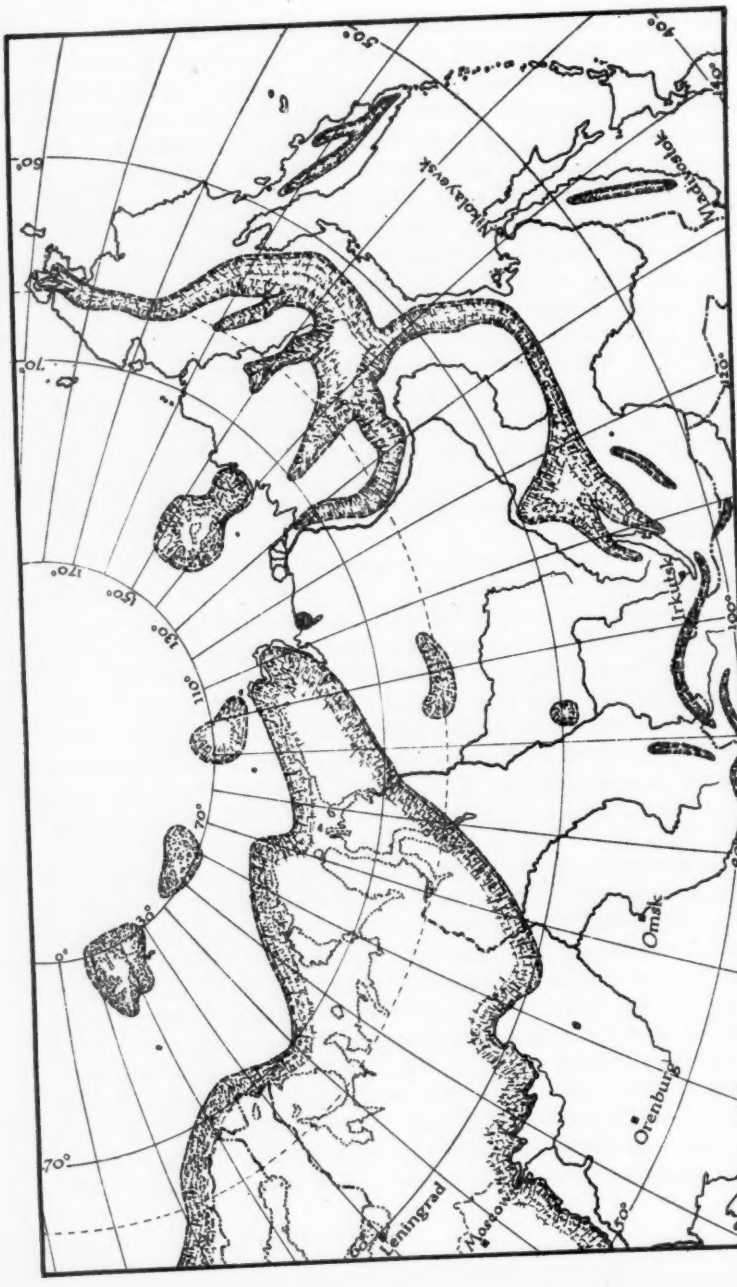

FIGURE 18.—*Areas glaciated in northern Asia during the Pleistocene*
Equal area azimuthal projection. Scale, 1 : 40 million.

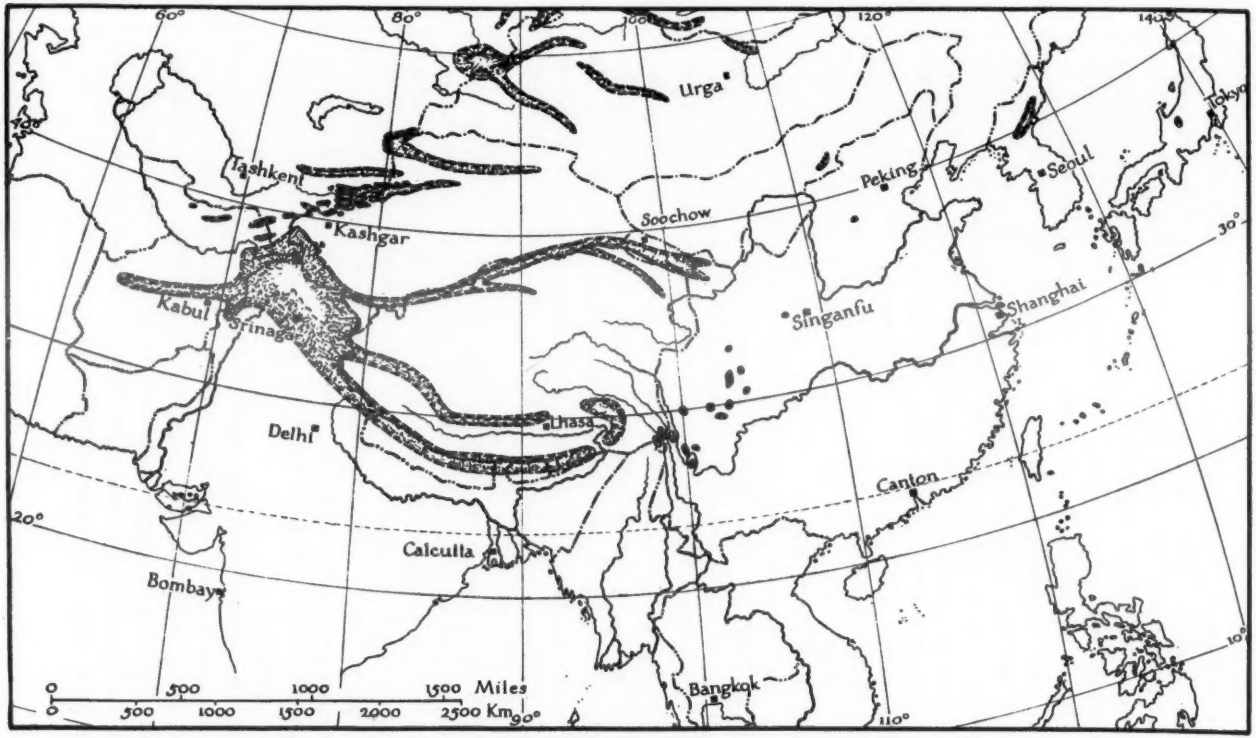

FIGURE 19.—*Areas glaciated in southern Asia during the Pleistocene*
Equal area azimuthal projection. Scale, 1 : 40 million.

The Himalaya and the Transhimalaya Mountains, the mountains and valleys of Kashmir, the Pamir Plateau, the Hindu-kush in Afghanistan, and the Kuenlun and connecting ranges in Tibet and Sinkiang were heavily glaciated (Diener, 1896; Hedin, 1905; 1907; 1910, page 3; 1922; Oestreich, 1906; Burrard and Hayden, 1907–1908, page 192; Schultz, 1916; Sobolewski, 1918; Dainelli, 1922; Ward, 1927; Grinlinton, 1929). In Kashmir and Pamir the ice-sheets attained large dimensions.

The Alai Mountains, in latitude 39 degrees north, longitude 70 degrees east; the Tienshan Mountains, in latitude 42 degrees north, longitude 75 to 85 degrees east; the Alexander Mountains, in latitude 43 degrees north, longitude 74 degrees east; and the Ala-tau Mountains, in latitude 45 degrees north, longitude 80 degrees east, as well as other ranges, carried numerous glaciers (Friedrichsen, 1908; Machatschek, 1912; Merzbacher, 1913; Muschketow, 1918; von Klebelsberg, 1922; Prinz, 1927). The Altai Mountains, in latitude 50 degrees north, longitude 85 to 90 degrees east, were widely covered with ice (see Granö, 1907; Fickeler, 1925; Tronow, 1925; Berkey and Morris, 1927*a*; Padurov, 1927; Schultz, 1928). So also were the Sayansk Mountains, in latitude 53 degrees north, longitude 90 to 105 degrees east (Obruchev, 1926; Preobrajanski, 1927; von Reinhard, 1928; Lamakin, 1928). Tannu Ola, in latitude 50 degrees north, longitude 95 degrees east, the Kentei Mountains, in latitude 49 degrees north, 108 degrees east (Moltschanow, 1918), and other ranges carried small glaciers. The Vitim Plateau, east of Lake Baikal, and the mountains east and north of the lake were widely glaciated (Hausen, 1925; Obruchev, 1926; see Antevs, 1928, page 4).

Small glaciers were formed in western Asia during the Quaternary period in several mountains. In early Pleistocene time there were glaciers on the highest parts of Mount Lebanon, in Syria, and perhaps also on the adjacent Mount Hermon (Blanckenhorn, 1914, page 39). In eastern Turkey (Armenia) and Transcaucasia several mountains supported glaciers (Oswald, 1912, page 19; Kharajian, 1915, page 35; Zdaniewicz, 1917). Some of them, including Mount Ararat, now bear small glaciers.

In Asia Minor Pleistocene glaciers were formed only on Mount Olympos, in latitude 40° north, longitude 29° 15′ east, south of Constantinople (Philippson, 1918, page 19; 1919, page 230). On the highest peak of the Ilghaz Daghi, in latitude 41 degrees north, longitude 34 degrees east, there are low ridges that possibly are glacial moraines (Czeczott, 1929). There are recent moraines on Agaios.

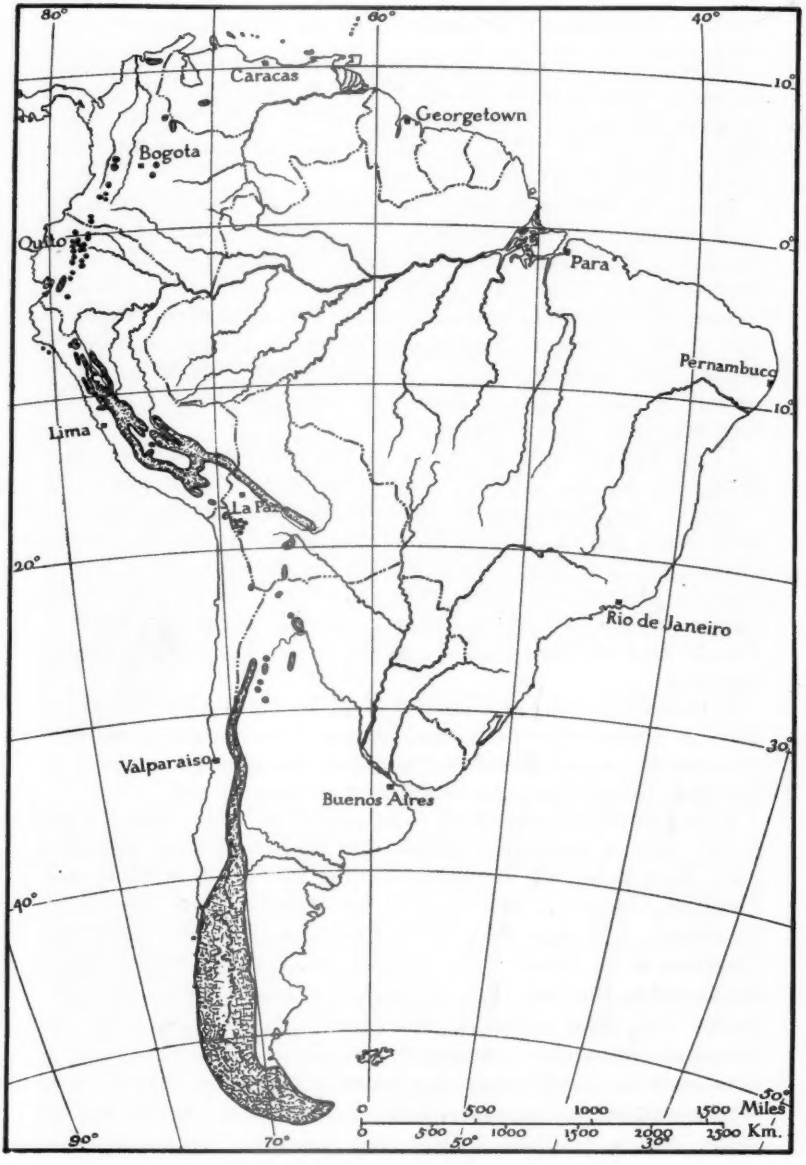

FIGURE 20.—*Areas glaciated in South America during the Pleistocene*
Equal area azimuthal projection. Scale, 1 : 45 million.

Pleistocene Glaciations in South America

Glaciers are now found on the high peaks and mountain ranges from northern Colombia down to Cape Horn. In southern Chile, between longitude 73° and 74° west and latitude 46° 30′ and 47° 30′ south and latitude 48° and 50° 30′ south, there are two enormous ice fields that some geologists have called ice-sheets.

During the Pleistocene epoch there were more extensive glaciers in these mountains and in many others. There were two and perhaps three Pleistocene glaciations, but only locally has distinction been made between them. Most of the available maps and statements refer only to areas glaciated at one time or another. The extent of the modern as well as the Pleistocene glaciation is shown on a map prepared by Sievers (1911, map on scale of 1:30 million; 1914, page 64, same map on scale of 1:37.5 million). Most of the data shown on our map have been taken from those of Sievers.

In the Sierra Nevada de Mérida, in Venezuela, the glaciers formed during the Ice Age extended much lower than those of today. In Colombia, also, the glaciers descended far below their modern remnants in the Sierra Nevada de Santa Marta, Páramo del Almorzadero, Sierra Nevada de Cocui, Ruiz, Tolima, Páramo des Sumapez, and at Bogota (Sievers, 1911; Stutzer, 1925; 1927, page 311). On the other hand, some mountains in southern Colombia and just across the frontier in Ecuador that now carry glaciers seem not to have borne any in Pleistocene time.

In Ecuador, on and just south of the Equator, about fifteen mountains show ice action below the present glaciers. Five ranges in southern Ecuador that carried glaciers in Pleistocene time carry none at present. The glaciated mountains are enumerated on Sievers's map.

From latitude 4 degrees south to latitude 6° 30′ south, there is a gap in the chain of Pleistocene glaciers, but glaciers occurred without a break down to latitude 19 degrees south in the Cordillera Blanca and Cordillera Central on either side of the Maranon River (Sievers, in Steinmann, 1929, page 261); in the Cordillera Occidental and in the Cordillera de los Andes, nearly inclosing the Ayacucho Valley; and in the Cordillera Real and other ranges east of Lake Titicaca. There are glaciers now along nearly the whole length of these ranges, but the former glaciers reached considerably lower levels. Several high mountains south of Lake Titicaca show traces of Pleistocene glaciers, as do other mountains that now carry no glaciers in southern Bolivia and the border regions of Chile, Bolivia, and Argentina. In northwestern Argentina several high mountains carried local Pleistocene glaciers.

All now carry glaciers. Sierra Famatima, in latitude 29° 30′ south, longitude 67° 30′ west, presents, according to Schmieder (1925, page 276), only a few cirques, not widely distributed traces of former glaciers.

From latitude 26° 30′ south down to Cape Horn the high Cordillera on the border between Chile and Argentina was extensively glaciated. The glaciation increased markedly at about latitude 35 degrees south, and it appears to have formed an ice-sheet in the southern part of the range. Modern glaciers are numerous and large in this belt, especially between latitude 46° 30′ south and 50° 30′ south. The Pleistocene ice may have reached the inner side of the island of Chiloé, south of which it reached the sea, which checked its further progress (Bruggen, 1929, page 26).

On the Argentinian side the glaciers flowed down the valleys scooping them out and building morainic dams, behind which many large lakes are now ponded. In the region about Aconcagua the terminal moraines of the former glaciers are seen at altitudes of about 2,500 meters (8,200 feet), but from this region southward their altitudes decrease rapidly, so that in about latitude 40 degrees south they are found at altitudes between 1,000 and 700 meters (3,280 and 2,300 feet) (Kühn, 1927, page 62). Still farther south the glaciers coalesced to form an ice-sheet that spread beyond the mountain range, and south of the Gallegos River, in latitude 52° south, the ice reached the Atlantic Ocean. Thus it probably covered all land south of latitude 52 degrees south (Fenton, 1921, map; Kühn, 1927, page 62).

The Falkland Islands were not glaciated (J. G. Anderson, 1906, page 101).

Pleistocene Glaciations in Africa

Of the large continents, Africa contained the smallest total area of glacier ice during the Pleistocene. Glaciers appear to have been formed only in the Atlas Mountains and on the high summits in the equatorial region. They were not formed on any range in South Africa (Rogers, 1922), and because of then small rainfall were probably not formed on the ranges in Abyssinia, although a number of those ranges rise above 3,000 meters (10,000 feet).

During the Pleistocene epoch glaciers seem to have been formed in large parts of the Great Atlas where none are known at present. Traces of ancient glaciers have long been known in the Reraïa Basin, in latitude 31° north, longitude 7° 45′ west (Maw, 1872), where they descended to the level of 2,100 or 2,000 meters (about 6,600 feet) (de Martonne, 1924). Traces of glaciers are recorded from Telouet, in latitude 31° 20′ north, longitude 7° 20′ west, and Goundafi, in latitude

31° north, longitude 8° 30′ west (Gentil, 1924; Wattier, 1926). In Algeria, at the mouth of the gorge El Kantara, in latitude 35° 15′ north, longitude 5° 40′ east, moraines of Pleistocene glaciers have been observed (Grad, 1872).

Of the high mountains in Equatorial East Africa, Kenya, Kilima Njaro, and Ruwenzori, though they lie near the Equator, now carry glaciers. During Pleistocene time these glaciers extended much farther down the slopes and valleys (Antevs, 1928, page 49; Nilsson, 1929*a*). A fourth mountain, Mount Elgon, which now bears no permanent ice, also carried Pleistocene glaciers that descended to a level of about 3,300 meters (10,800 feet), as shown by moraines and striæ (Nilsson, 1929, 1929*a*).

Pleistocene Glaciations in Australasia

The area covered by Pleistocene glaciers in Australasia was evidently not large. In the Australian continent glaciers were formed only on the Kosciusko Tableland, in southeastern New South Wales, in latitude 36° 20′ south, longitude 148° 15′ east (Süssmilch, 1922, page 219; also Antevs, The Last Glaciation, page 10). Glaciers were formed during two or three epochs. During the first epoch ice capped the entire plateau, which covers an area of 200 to 260 square kilometers (80 to 100 square miles). During the last age of ice formation only valley glaciers, one or two miles long, developed.

In Tasmania three stages of glaciation are more or less apparent (Nye and Lewis, 1928, pages 25-28). During the first stage the ice was far more extensive than during the last, covering fully one-third of the island. Ice-caps and glaciers covered the mountains in the western part of Tasmania, most of the central plateau, and the summit of Ben Lomond, in the northeastern part, in latitude 41° 30′ south, longitude 147° 45′ east, and coalescing glaciers filled the western valleys and at places reached the sea. Later, the tableland, which had been smoothed by ice, was deeply channeled and dissected by valley glaciers. Still later small hanging glaciers produced cirques at high levels. In modern time snow banks persist in some of the mountains through the year. No map showing Pleistocene glaciation in Tasmania appears to be available, and the data at hand are hardly definite enough to permit the construction of one.

New Zealand is the only country in Australasia in which there are now real glaciers. During the Pleistocene epoch glaciers were formed in the high alps on a large scale at least twice (Morgan, 1926, pages 278-280). The extent of the Pleistocene glaciation has been shown on a map compiled by Marshall (1911, page 48), which, however, shows no

distinction of glacial epochs. The map here given is compiled from Marshall's map and from other data (Morgan, 1926, page 278; Ferrar, 1928; Speight, 1928, page 2). The glaciation covered the mountainous country and the intermediate lowland in the northwestern half of the South Island, besides the lowland strip of the Westland and small parts of the Canterbury Plain. The ice consisted of a network of glaciers, rather than a continuous cap. It occupied nearly one-third of the island. Many glaciers in the Westland descended to or below the present sea level.

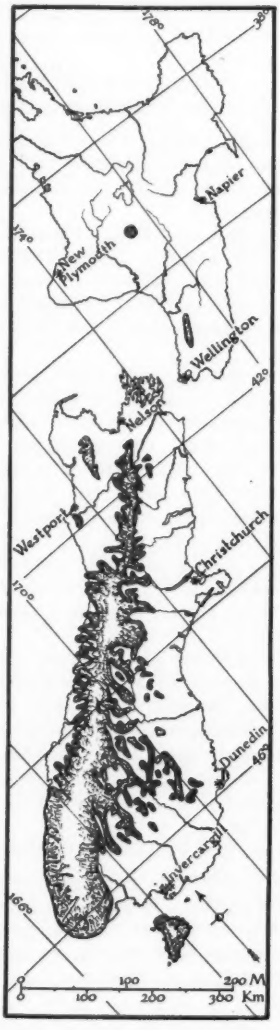

FIGURE 21.—*Areas glaciated in New Zealand during the Pleistocene*
Scale, 1 : 10 million.

Stewart Island, which lies south of South Island, was probably heavily glaciated (Morgan, 1926, page 278).

The extent of the Pleistocene glaciation on North Island is unknown, for possibly its traces have been obliterated by postglacial volcanic eruptions. However, glaciers were formed in the higher parts of the Tararua Range (5,154 feet high), at the south end of the island (Adkin, 1912). Glaciers may also have descended the sides of the volcanic cone Ruapehu (9,175 feet), whose crater, a mile wide, now contains a glacier (G. Taylor, 1927).

In New Guinea traces of former glaciation have been found on Mount Wilhelmina, in latitude 4° 15′ south, longitude 138° 15′ east; on Mount Carstensz, in latitude 4° south, longitude 137° 15′ east; and on Mount Soruvaged, in latitude 6° 30′ south, longitude 147° east, as well as near sealevel at the west end of the Huon Gulf, in latitude 7° south, 147° east (Antevs, 1928, page 52; Behrmann, 1919, page 375). Also Mount Idenburg, in the same range as Mount Carstensz, presents

old cirques (Behrmann, 1928, page 197). Even today the summits of Wilhelmina, Carstensz, and Idenburg carry small glaciers (Behrmann, 1928, page 198).

Mauna Kea, Hawaii, was capped by ice during the Pleistocene.

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SWINGING SEALEVEL OF THE ICE AGE[1]

BY REGINALD A. DALY

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DATING AND CAUSES OF SOME EUSTATIC SHIFTS OF SEALEVEL

SUBJECTIVE NAMING

The geological timetable is a thing of shreds and patches, the product of the shifting views of the nineteenth century about the proper subdivision of geological time. Usage is not uniform. Logically the Pleistocene ("most recent") period includes both Recent time and Quaternary time, which covers the so-called Glacial period. Geology has been developed by men living in the middle latitudes of the Northern Hemisphere. For those leaders of thought the Glacial period is of the past. For a geologically minded penguin of Antarctica the Glacial period is here and now. The truly objective philosopher must agree with the penguin: the earth as a whole is something like halfway through

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This paper forms part of the symposium on the centenary of the Glacial theory.

the Glacial period. Land ice now mantles 15,000,000 square kilometers, as against 30,000,000 square kilometers, or 6 per cent, of the earth's surface when the ice-caps were last at maximum.

POSITION OF SEALEVEL ON AN ICE-FREE EARTH

Through most of Tertiary time the globe seems to have been too warm to bear extensive glaciers. Where was sealevel then? Where would it be if the Antarctic and Greenland ice should melt? Let us examine the second question.

The area of the Antarctic ice-cap above sealevel is nearly 13,000,000 square kilometers. Its average thickness is unknown, but may be estimated as between 750 and 1,500 meters. Accordingly, the melting of the ice, with density taken to be 0.9, would raise sealevel, on a perfectly rigid earth, everywhere by 24 to 48 meters, or, say, 80 to 160 feet. However, the planet is both compressible and very weak against long-continued pressures. Hence immediately, and also after the lapse of some time, it would yield to the load of water added to the ocean, while Antarctica, freed from its heavy load of ice, would rise. The globe would thus tend to reach hydrostatic equilibrium throughout its mass.

The ultimate depression of the floor of the open ocean would be of the order of 5 to 10 meters; the corresponding net rise of sealevel along continental shores, outside of Antarctica and Greenland, would be of the order of 19 to 38 meters.

Simultaneous melting of the Greenland ice-cap would add about 10 per cent to these figures.

The total ultimate rise of sealevel along most continental shores comes out as 21 to 42 meters. The best estimate is probably 30-35 meters. Oceanic islands rigidly attached to the ocean's floor would sink with it, and there the shift of strandlines would be 26 to 52 meters. For this and other reasons (including elastic and gravitational effects) the relative shift of sealevel would not be quite uniform over the earth; neither would perfect uniformity be expected in the case of each of the greater shifts during Quaternary time.

If, then, for a long time before Quaternary glaciation began, the level of the ocean was higher than now, strandlines were engraved on the continents and the deep-sea islands then existing. Have we any relics of those marine benches and terraces? The question is not easy to answer. Later erosion could not fail to destroy or obscure many of the strand-marks. Warping of the earth's crust has tended to change the levels of bench or terrace, so that their original systematic accordance is not to be readily demonstrated. As a matter of fact, in parts of the earth

there are remnants of old strand-marks with respective general elevations of 50 to 60, 30 to 35, and 15 to 18 meters. Whether any of these sets of determinations represents the normal sealevel for an ice-free earth is a problem for future investigation. Conceivably the strand-marks standing at the level of 30 to 35 meters correspond to the pre-Glacial sealevel, while the lower set of marks were made on the lands during a fraction of Pleistocene time, when the Antarctic ice-cap had about half its present volume. On the other hand, we shall later note a quite different explanation of the set of marks at the level of 15 to 18 meters (50 to 60 feet).

POST-GLACIAL GENERAL SINKING OF SEALEVEL

Less speculative is the assumption of a world-wide, or, as technically expressed, eustatic, change of sealevel since the ice-caps of Europe and North America disappeared. Personal study of shorelines of the Atlantic, Pacific, and Indian ocean basins, together with compilation of data published by others, has led me to suggest such a recent general sinking of sealevel to the extent of a few meters. To measure the exact amount of the sinking at any locality demands accurate knowledge of the relations of wave-cut bench or wave-built terrace to the sealevel at the epoch of its formation, and this datum is seldom to be obtained with certainty. However, the described lowering of sealevel appears to have averaged about five meters.

The recent negative movement of sealevel has been speculatively explained by a simultaneous increase of the existing ice-caps. During the late Neolithic age of Europe the average climate of the Northern Hemisphere at least was decidedly warmer than at present. About 3,000 years ago the earth's climate seems already to have attained its existing average character. Assuming the change from warm to cooler to have centered around the epoch of about 4,000 years ago, and that then the Antarctic ice-cap was thickened by 150 to 200 meters, we should be able to account for the world-wide five-meter drop of sealevel.[2]

[2] G. de Geer: Ymer, vol. 45, 1925, p. 1 (abstract by E. Antevs, Geog. Review, vol. 16, 1926, p. 170). R. Gradmann: Hettner's Geog. Zeit., 1924, Heft 4, pp. 249, 260. R. A. Daly: Geology of Saint Helena Island. Proc. Amer. Acad. Arts and Sciences, vol. 62, 1927, p. 80, with references.

In addition to the extensive data compiled and used in the preparation of the paper last mentioned, new discoveries of what appears to be the five-meter strand-mark have been reported from the Texas coast (Deussen); Jamaica (Matley); Gibraltar (Jessen); Mediterranean coast of France (Depéret and Denizot); the Red Sea coast and Zanzibar (Crossland); along 3,000 kilometers of the South African coast (A. V. Krige, who has carried out the most complete relevant field study ever undertaken in any one region); New South Wales (Harper); Fiji and Tonga Islands (Ladd and Hoffmeister); Marquesas Islands (Chubb); Nauru Island (Bohne); Oahu Island (Pollock); New Zealand

QUATERNARY OSCILLATIONS OF SEALEVEL

Much greater eustatic shifts of sealevel must have accompanied each glaciation and deglaciation (melting of ice) during the pre-Recent, Quaternary time, the Ice Age as ordinarily understood. Both in Europe and North America the Quaternary ice-caps waxed at least four times and waned at least four times, though unequally, an earlier set of glacial stages being separated from a later set by an exceptionally long interglacial stage, when the earth was perhaps entirely ice-free (Toronto-Eemian deposits). Probably the changes were respectively simultaneous in the two continents. Thus the following correlations have been made: Jerseyan drift with the Günz of Europe; Kansan drift with the Mindel; Illinoian drift with the Riss; and Wisconsin with the Würm. Each glacial stage meant world-wide sinking of sealevel. Each of the interglacial stages, like the post-Glacial stage, was ushered in by a world-wide rise of sealevel.

The last, Wisconsin-Würm, oscillation of level can be discussed quantitatively. At least one of the earlier swings was of the same order of magnitude.

Only within the last few decades have required data been assembled and that only partially. In 1842, only two years after Louis Agassiz published his "Études sur les Glaciers," Maclaren guessed the lowering of sealevel in consequence of glaciation to have been 350 to 700 feet (107 to 213 meters). Many other estimates have since been made. The latest and probably the most reliable is that of Antevs, who gives 83 to 93 meters for the deepening of the ocean through the melting of the ice of the Wisconsin-Würm stage.[3] The larger value derives from the as-

(Ongley and Macpherson, Bartrum); Henderson Island (Aurousseau); Andaman, Chagos, Maldive archipelagoes, Persian Gulf, coast of India (Sewell).

Recent emergence of amounts that seem to correspond is described by W. M. Davis in his "The coral reef problem" (1928), at the following oceanic islands: Rocas Island, off Brazil; Aldabra, Silhouette, and Mahe Islands, Indian Ocean; Ovalau, Ono-i-Lau, Solo, and Vatu Vara Islands of the Fiji group; McKean, Enderby, Phœnix, and Birnie Islands of the Phœnix group; Niau, Rangiroa, and Matahiva Islands of the Paumotu group.

Concerning the date of the five-meter shift of sealevel and the Pleistocene shifts in general, see important papers by G. Dubois (Annales soc. géol. du Nord, vol. 49, 1925, p. 120, and Bull. soc. géol. France, vol. 25, 1925, p. 857, both with references). Compare C. E. P. Brooks, "The evolution of climate" (London, 1925), p. 164.

[3] E. Antevs: The last glaciation. Amer. Geog. Soc., Research Series No. 17, 1928, p. 81. Earlier estimates of the range of oscillation are tabulated in Daly's 1925 paper of reference 3. The maximum lowering of sealevel by the glaciation of the lands, perhaps in Kansan time, may have well exceeded 80 meters. This maximum may be in mind when one is thinking of the depth to which rivers could sink their channels in the emerged banks and shelves of the glacial stages, but the maximum is not so important as a basis for estimating the extent to which the low-level waves and currents cut down into and smoothed the banks and shelves during the Wisconsin stage. In the latter problem the lower figure of 60-70 meters seems to be a better datum.

sumption that the Antarctic ice-cap attained its maximum volume simultaneously with the ice-caps of the Northern Hemisphere and has since diminished by a certain amount. A deepening of as much as 100 meters may not be out of the question.

For the remaining discussion let us assume the round figure of 80 meters (262 feet, or 47 fathoms) for the depth of the water which has been returned to the ocean since the epoch, some 30,000 years ago, when the ice of the Wisconsin-Würm stage began its slow melting.

Some Consequences of the last great Melting

Distortion of the solid earth and of the geoid

The transfer of water substance from the lands to the ocean through melting of the ice-caps of course raised the surface of the ocean everywhere and, in addition, had other complicated effects on levels. These latter effects were of two kinds: one immediate, the other delayed. The immediate effects were, in their turn, of two kinds, including the purely elastic distortion of the whole globe, and, secondly, the distortion of the geoid, or sealevel, surface itself.

The prompt, elastic reshaping of the earth was general, but it most affected levels in and near the glaciated tracts. The rocky surface at the center of each major glaciated tract, when relieved of the heavy ice-cap, rose several scores of meters, and at the edge of the tract nearly one-third as much. For several hundreds of kilometers outside the edge of the tract the rocky surface was elastically superelevated to a corresponding degree. It is possible that in this peripheral belt the earth's crust had been somewhat bulged upward because of earlier viscous outflow of the subcrust material under the weight of the ice-cap. If so, the peripheral bulge itself was elastically uplifted when the ice melted, and thus for two reasons a fairly broad belt of ground just outside the terminal moraine was elevated above the level of final equilibrium. Outside these peripheral belts of superelevation the rocky surface of the globe was elastically depressed somewhat below the level of final equilibrium.

The weight of water added to each ocean basin similarly caused an immediate elastic sinking of the floor of that ocean, in greatest amount near the center of the basin.

The other immediate effect on levels, that on the geoid, was smaller than the elastic effect and, with reference to the earth's center, was in the opposite sense. Thus the water substance removed from each glaciated tract no longer by its own mass attracted the ocean water to-

ward the center of that tract; hence the sealevel sank at the center of the tract. For the same reason it sank about one-third as much at the edge of the tract. Beyond a moderately broad belt outside each of the glaciated tracts, the sealevel rose slightly because of the same disturbance of the gravitational field by removal of water substance from the continents.

Further immediate warping of the geoid was caused by the attraction of the water just added to the ocean basins. This cause of change of sealevel was small, but would have to be considered in a full statement of the complex story.

For thousands of years after the ice-caps melted, the elastic warping of the earth's crust and the gravitational warping of the geoid persisted, though by slowly diminishing amounts. In part these effects were gradually annulled as the earth yielded plastically—by flow of material in its deep interior—under the negative loads of the glaciated tracts and under the positive loads of the water added to the ocean basins. During the last 20,000 years or so, and especially during the 10,000 years of post-Glacial time, deep-seated material of the earth's body has been slowly flowing out of the suboceanic sectors. Much of this material has moved into the glaciated sectors. The plastic yielding has already gone nearly to the limit set by hydrostatic equilibrium in the earth. The rocky surface of each glaciated tract has therefore risen; the peripheral belts, which had been elastically superelevated, have correspondingly sunk. The outward flow of deep-seated material from the suboceanic sectors has lowered each ocean floor. The amount of the lowering is unknown, but there are reasons for believing it to have been as much as 15 to 20 meters. Of course, the water level followed down the ocean floor; hence the shorelines on the continents, well outside the glaciated tracts, are now lower than the shorelines existing just before the post-Glacial, plastic distortion of the globe took place. Inasmuch as the oceanic islands were carried down with the suboceanic crust, the strandlines on their shores have not been relatively displaced.[4]

Because of the strength of the crust, all parts of the ocean floor could hardly have sunk uniformly through the plastic distortion; nor did this leave all parts of the continental areas of the crust undisturbed. Therefore the strandlines that were engraved along the continental shores before the slow plastic distortion (the so-called isostatic adjustment) took place should not now be at exactly the same height above present sealevel; yet it seems possible that we have here an explanation of a

[4] R. A. Daly: Amer. Jour. Science, vol. 10, 1925, p. 301. F. Nansen: The Strandflat and isostasy, Kristiania, 1922, p. 233, etc.

marked strandline, at height of 50 to 60 feet (15-18 meters), along the Atlantic coastal plain of the United States south of New York and along at least 3,000 kilometers of the South African coast.

In any case the earth's elastic and non-elastic distortion, caused by the melting of the Pleistocene ice-caps, is clearly an important set of effects, the analysis of which is worth the best efforts of geologist and geophysicist.

It should be noted, too, that each deglaciation (melting of ice) of the long Pleistocene period caused distortion in the same sense as that described for the last melting; also, that each glaciation caused bodily distortion of the earth in the reverse sense. Hence during the Ice Age the earth was reshaped at least eight times.

Outside of the glaciated tracts, the effects of distortion, whether of the solid earth or of the geoid, were, in relation to the vertical displacement of strandlines, decidedly subordinate to the effect of the mere addition of water to the ocean when the ice-caps melted. Similarly, when the Wisconsin-Würm ice-caps were of full size, the sealevel over most of the earth was not far from 80 meters lower than at present. We shall glance at some consequences of this fact.

LOCAL CHANGES ON THE LANDS

The lowering of the general baselevel forced the rivers to sink their beds well below the existing sealevel, especially in the softer materials of the old land and in the unconsolidated sediments of the shelves and large deltas. Such down-cutting was in general probably cumulative during the four or more glacial stages of the Ice Age. The final late-Glacial drowning of these deepened valleys largely explains features like the existing submarine channel of the Hudson and also the abundance of good harbors along the continental shores of the world.

With each shallowing of the shelf seas, epicontinental seas, human migrations from continent to continent and from continent to island were facilitated.[5] If the men of the last glacial stage lived in the river bottoms then being excavated in the deltas of Nile or Euphrates, the relics of their culture are doubtless now buried under the silts since brought down by the respective rivers. Incidentally, too, archeologists may yet find at least partial explanation of harbor sites, now dry or even far inland, in terms of the 5-meter drop of sealevel about 3,500 years ago. The problem is illustrated by the ancient Eridu of Babylonia, now 190 kilometers inland.

[5] One of the best discussions of this consequence is that by the late J. V. Daneš, Scot. Geog. Mag., vol. 41, 1925, p. 289.

CHANGES IN THE CONDITIONS OF MARINE LIFE

We turn now to a third group of consequences of the Quaternary swings of level—the effects on marine organisms, especially the shallow-water forms.

Just before the first glacial stage the deposition of inorganic and organic detritus had completed broad or narrow shelves or terraces along all sea shores. At present the water on a typical shelf, facing continent or old island, deepens rather rapidly from the beach outward; then more slowly. At the depth of 40 to 50 fathoms, or 75 to 95 meters, the surface of the shelf begins to drop rapidly to the deep, general level of the ocean floor. On account of erosion while the sealevel was lower than now, the profiles of the pre-Glacial shelves were somewhat altered, so that we can not be sure that any profile is now in equilibrium with waves and currents. However, we shall not make any essential error if we suppose that the break of slope of each well developed, pre-Glacial shelf was situated at the depth of 75 meters. The break of slope for most of the submarine landless banks would be at nearly the same depth.

With the onset of each of the four glacial stages, the sealevel began to sink, and for some thousands of years it continued to go down, until the volume of land ice reached its maximum. Each time, the level sank about 80 meters or a large fraction of 80 meters. At least twice the coastlines were moved out nearly or quite to the breaks of slope, the outer "edges" of the shelves and banks. During this slow process, then, the waves of the whole ocean were beating on little else than mud and sand, the dominant superficial materials of shelf and bank. The water was murky with mud to a degree which can not be matched under the normal conditions of a stable sealevel. Many shallow-water species of animals sensitive to the muddying of water were affected more or less seriously.

ORIGINATION OF THE EXISTING CORAL REEFS

As the sea withdrew, a kind of elutriation, or sorting, of the sediment on shelf and bank took place. The fine muds were specially stirred up and in large amount carried out to deep water. The coarser sand was less readily removed and became concentrated in the form of a superficial layer on shelf or bank.

Because each of the four accumulations of ice on the continents was nearly at maximum for several tens of thousands of years, the waves beat long near the breaks of slope, about 75 meters below present sealevel. There especially was the removal of mud prolonged, with a corresponding concentration of coarser detritus, including the elutriated sand

and also the shells and skeletons of the shore-dwelling organic species then existing.

The result was a considerable cleansing of mud from the old shelves and banks. Since the sealevel rose for the last time, the water on shelf and bank has been relatively clean, much less charged with suspended mud than it was in pre-Glacial time. During post-Glacial time, therefore, those shallow-water animals which are killed by abundant storm-raised mud have been enabled to live and multiply at an extraordinarily high rate. The reef-building corals illustrate the case. On account of their importance as rock-bodies, the problem of the living coral reefs appeals to any naturalist. Still more manifestly this problem continues to engage attention because of the prestige of Darwin's famous speculation on the subject, with its deduction of widespread instability of the earth's crust. Let us briefly consider the conditions for life for this one group of shallow-water animals, the corals, during the Pleistocene period.

Each existing atoll or barrier reef is characteristically wall-like. On the lagoon side the water is usually 50 to 75 meters deep and the reef rises more and more steeply from this depth. On the side toward the open ocean the face of the reef commonly drops off at a rapid rate into water which is thousands of meters deep. In such a case the structure rises from a belt which is nearly or quite identical with the break-of-slope belt characteristic of a detrital shelf or bank.

No atoll or barrier reef of pre-Glacial date of origin has yet been demonstrated. Because the water at the edge of the normal pre-Glacial shelf or bank was much too deep for the growth of these shallow-water species, and because of the lethal effects of storm-stirred mud, we may well doubt that either atoll or barrier reef of the kind just described could have been formed in pre-Glacial time. Doubtless fringing reefs existed, but their outward growth in the face of the destroying waves may have been decidedly limited by the muddiness of the shelf waters of the time.

Not only did each glaciation of the continents mean great accentuation of this mud-control; it meant also a prolonged, though temporary, general absence of hard bottom on which the corals could build stable structures. And, thirdly, it meant cooling of the oceans. Merely moderate cooling kills the reef-building corals, and this must be rated as another important reason why reef-growth was greatly inhibited during any one of the glacial stages. One can hardly be certain that a single reef was then thriving in the modern way, at the modern rate. Of course, the reef corals were not entirely extinguished. After each glacial stage the coral larvæ could issue from warm, sheltered inlets of the sea and

with relative speed colonize the appropriate shallows. New reefs could thus be built wherever the warmer currents bore the larvæ in sufficient abundance.

The warming of the world climate long preceded the close of the last principal melting of land ice. The accompanying rise of sealevel was extremely slow, so slow as to permit extensive colonization and inception of new reefs at the outer edges of shelf and bank before the water got too deep for coral growth. The corals throve best at or near the edges; that is, in the case of the shelves, along the shores of the coastal plains, which were then dry because of the previous withdrawal of water from the ocean. Three reasons for this statement may be mentioned:

(1) Along those low-lying shores and sites of shallows the deleterious mud had been largely removed during the prolonged time when there was thick ice on the lands (tens of thousands of years). Thus, as we have already seen, a comparatively clean, sand-shell bottom was prepared for the colonizing larvæ.

(2) On the side toward the open ocean the water of the incoming waves and currents was almost entirely free from mud, and, like the waves and currents now bathing the outside of an existing atoll or barrier, were specially charged with the food and free oxygen which are necessary for the life of corals and their associates in reef-building.

(3) Finally, there is some reason for supposing that a hard bottom, such as is favorable to the most successful rooting of a coral reef, would be formed at the edges of the shelves and of any emerged banks; for the recently emerged sands of Florida and other tropical regions have been lithified to a large extent. Moreover, even between tide-marks, siliceous and carbonate sands are now being converted into rather strong "beach rock" at intervals along our tropical beaches.

Hence, along the outer edges of continental and island shelves and detached banks, the conditions for the establishment of reefs are regarded as having been particularly favorable. It is usually in just such situations that the reefs are thriving best today, as barriers and atolls. We have already noted that the continued upward growth of the reefs was insured by the slow rate at which sealevel rose on shelf and bank.

Vigor of growth for fringing reefs also had been secured by the special conditions of the Glacial period. The removal of much mud from shelf and bank and the moderate lowering of the surfaces by wave erosion at the lower levels caused the water on the post-Glacial and

interglacial shelves and banks to be abnormally clean. For this, among other reasons, isolated coral knolls have also grown up on non-barriered, detrital shelves, as well as within the greater atoll and barrier-reef lagoons.

That the pre-Glacial reefs grew with less vigor than the living reefs is further indicated by the strictly limited volumes of true reef structures among the uplifted limestones of the tropical belt. Coralliferous limestones are there in quantity, but few, if any, are shown to have been fast-growing, powerful reefs of the type represented in the living atoll, barrier, or fringe.

On the other hand, atoll, barrier, and fringing reefs of interglacial dates of formation are likely to have been formed according to the mechanism outlined for the post-Glacial living reefs. A few elevated atolls and barriers of the southwest Pacific may be examples.

To summarize: The Glacial-control theory, based upon the Pleistocene, eustatic oscillations of sealevel and the accompanying changes of world temperature, seems to account well for the wonderful structures which are still being built by corals, though these can not thrive in water deeper than 10 to 20 meters. In order to explain the heights of the living reefs, heights which commonly reach 75 or more meters, a rise of sealevel on the foundations of the reefs must be postulated. Melting of the Quaternary land ice appears to provide amply for the required change of level.[6]

A complete testing of the theory is a subject much too broad for present consideration, but a few tests may be mentioned.

First, the supreme test of prophecy. The theory foretold that material of the continental shelf should be found at the approximate depth of 75 meters under any coral knoll which has grown up in the central part of the broad lagoon back of the Great Barrier Reef of Australia. In 1926 a bore-hole was put down through such a knoll and disclosed sand and ooze typical of a continental shelf, beginning at the depth of 241 feet, or 73 meters, and continuing to the bottom of the hole, at 183 meters. Above the 73-meter level the material was coralliferous.

[6] Most of the leading elements of the writer's Glacial-control theory are summarized in the American Journal of Science, vol. 48, 1919, p. 136, where references to older statements may be found. The description of the theory by W. M. Davis in "The coral reef problem" (Amer. Geog. Soc., Spec. Pub. No. 9, 1928) is inaccurate in some of the essentials. Thus based on wrong premises, his argument has led Davis to the statement (page 285) that the Glacial-control theory is of "small value." The main conclusion of this monograph is favorable to the Darwin-Dana theory of subsidence; and yet Davis, like all of his predecessors, has not been able to annul any of the more or less obvious, and apparently fatal, objections to the Darwin-Dana theory.

Beneath that level not a single fragment of coral "in place" was reported.[7]

The theory foretold a submarine thickness of about 75 meters for the coralliferous limestone on the top of the Bermuda bank. A boring there made found the fragmental rock of a Tertiary volcano at the depth of 245 feet, or 74.6 meters, below sealevel.[8]

The celebrated bore-hole at Funafuti was wrongly placed and can therefore afford no clear test of the rival theories of coral reefs.

The two borings here more useful show that crustal subsidence is not a necessary accompaniment of the upgrowth of coral reefs. Sayles has brought weighty evidence that the Bermuda bank did not sink during the whole Glacial period, a time of the order of one million years, and that in spite of the enormous weight of the pre-Pliocene (pre-Miocene?) Bermuda volcano on the earth's crust.[9] The small depth of the volcanic surface, a surface of erosion, below sealevel proves similar failure of subsidence during several millions of years. So it is with the Australian case. The development of the broad shelf at normal depth, whether under the warm, reef-bearing sea or farther south, where the water is too cool for coral growth, spells crustal stability for some millions of years.

The prolonged stability of the earth's crust under many reefs and many reef-free islands is shown by the nearly uniform elevation of the strand-marks made before the last eustatic drop of sealevel, the 5-meter shift. Evidently the reefs and islands bearing these marks have not budged much, if at all, during the last 3,500 years or so. When mapping the Island of Saint Helena I was much struck with this evidence of its failure to sink, even though its volcanic cone represents a gigantic load on the earth's crust. The width and normal depth of the island shelf indicates practically perfect stability of the mass for much more than one million years. Saint Helena is merely an example of many hundreds of such cases among the islands of the tropical seas.

Finally, prolonged crustal stability is demonstrated not only by the breadth and smoothness of continental and island shelves, as well as of isolated banks, but also by the close accordance of the depths of these features among themselves and with the depths of the larger reef lagoons. No theory of reefs involving crustal subsidence can account for

[7] M. Nathan: Geog. Jour., vol. 70, 1928, p. 541. Clearly the presence of shells of shallow-water foraminifera in the beds below the depth of 73 meters does not demonstrate subsidence.

[8] L. V. Pirsson: Amer. Jour. Science, vol. 38, 1914, p. 193.

[9] R. W. Sayles and T. H. Clark: Bull. Geol. Soc. America, vol. 36, 1925, p. 141.

these facts of submarine topography, nor for the flatness of the lagoon floors. On the other hand, the observed accordances of depth and the actual smoothness of lagoon floors could have been prophesied from the Glacial-control theory, if the theory had been developed before a single plummet sounded the tropical seas.

However, the described comparative stability of the earth's crust has evidently been limited both in time and space. During the Tertiary period, for example, regions like Fiji, New Caledonia, and the Philippines witnessed the breaking, warping, uplift, and subsidence of the crust on a large scale. In consequence of the subsidence, many stream valleys were drowned and as many embayments developed. The bays still exist and testify to the sinkings. But just as clearly the sinkings took place before the shelves and banks, now bearing coral reefs in these particular regions, were formed. The formation of each shelf and bank took much time, during which the earth's crust must have remained nearly or quite stable. The preferred theory assumes that the existing coral reefs originated after shelf and bank were essentially completed, and *a fortiori* long after the mountain-building and sinkings of the Tertiary epoch. From this point of view, to assume that the existing reefs grew steadily upward during those sinkings of the crust and have so persisted to the present day is to beg the question of origins altogether.

The headlands and strips of coast between the bays of the drowned regions were not strongly cliffed by the low-level waves of the Ice Age. A leading reason for this is the brevity of the low-level abrasion. In general, the Glacial-control theory can not be discredited because high cliffs are so rare along the shores of the reef-secreting ocean. On the contrary, the theory demands relatively softened seaward profiles along all coasts which are fronted by broad shelves or barrier lagoons of the observed depths; for, as we have seen, the preparation of shelf and barrier foundation requires long periods of time, during which subaerial slopes must have been well graded seaward by subaerial erosion. Meanwhile the headlands and interbay strips of coast were protected against strong wave-action by the fringing reefs of the pre-Glacial time, much as they are now protected by fringing reefs, or by barrier reefs, or by both types of reefs.

To summarize: The swings of sealevel during the Ice Age seem best to account for the present abundance of the reef-building corals and for the forms and location of the living reefs. Hence it is not necessary to assume very recent widespread distortion of the earth, such as is implied by Darwin's subsidence theory. No sound physical reason for

such distortion has been suggested. No sound theoretical reason can now be given for resting in the belief that this particular distortion of the globe ever took place. On the other hand, there is evident need of correlation between two utterly different processes in widely separated parts of our dramatic earth—between cold-engendered glaciation and the growth of the warmth-loving corals. No man liveth to himself. No part of our planet liveth to itself.

Conclusions and Applications

Nor is any geological or geographical problem in a water-tight compartment. The study of eustatic shifts of sealevel during the Pleistocene leads to speculative explanations of (1) various strandlines, now high and dry; (2) drowned channels cut in the continental shelves; (3) the origin of many harbors; (4) the rarity of traces of shore-dwelling Paleolithic man; (5) the living coral reefs. But these questions are interrelated and they become more truly appreciated when they are seen to be vitally connected with major problems of earth science.

For example, the displacement of shorelines by the glaciation or deglaciation of the continents is not merely the direct effect of substraction of water from the ocean or addition of water to the ocean.[10] The loadings and unloadings with ice or water have meant a complex, rhythmical distortion of the whole globe—a kind of deep-toned tune played on our earth. As the facts become clearer, we shall know much more about the distribution of strength and viscosity in the earth, about the mode of isostatic adjustment, and about the time needed to adjust the earth isostatically for a widely extended load on the surface. Each waxing and waning of the ice-caps was a great experiment performed in Nature's laboratory. If we can grasp the full meaning of any one of these experiments, we shall have gained priceless information concerning the earth's interior, where the key to so many fundamental questions of geology and geography lies hidden.

[10] After this paper was prepared for publication, Dr. E. Antevs kindly sent to the writer the manuscript of an important memoir on "Quaternary marine terraces in non-glaciated regions and changes of level of sea and land," since printed in the American Journal of Science, volume 17, 1929, page 35. Dr. Antevs also discusses the position of sealevel on an ice-free earth. He does not specifically note the complicated effects of the earth's elasticity and plasticity on the positions of strandlines in non-glaciated regions. In connection with Dr. Antevs's correlation of Quaternary marine terraces, see the recently published "Étude géologique de la Tunisie septentrionale," Tunis, 1927, pages 478, 481, 484, by M. Solignac.

P. A. Wagner (Trans. Geol. Soc. South Africa, volume 31, 1928, page 12) reports that the marked 100-foot bench on the west coast of South Africa was formed when the sea water was warmer than it is now in the same belt. Does this bench mark the position of sealevel on an ice-free earth?

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CLIMATIC ZONES AND PERIODS OF GLACIATION[1]

BY W. H. HOBBS

(Read before Section E of the American Association for the Advancement of Science, December 27, 1928)

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INTRODUCTION

The advance of thought concerning the climates of the earlier geological ages was long held in check by various erroneous notions which were the outgrowth of fundamental doctrines of the science, the fallacy of which had later to be proven. Of these fundamental doctrines were the Kant-Laplace theory of the origin of our planet, the doctrine of uniformitarianism wrongly interpreted, Croll's theory of the recurrence of glacial periods, and the conception of low polar air pressures and circumpolar whirls.

Because of the wide acceptance of the Kant-Laplace hypothesis, our earth was long supposed to have taken its later condition as a consequence of progressive surface cooling and congelation from a molten mass. When, therefore, the evidence for a period of glaciation within late geological time had been uncovered, it was but natural that this glaciation should be directly ascribed to a culmination of the earth's refrigerating process.

THEORIES OF QUATERNARY GLACIATION

When the theory of Quaternary glaciation was promulgated geologists were well aware that in the characters of fossil floras there were to be

[1] Manuscript received by the Secretary of the Society January 21, 1929.
This paper forms part of the symposium on the centenary of the Glacial theory.

found the evidence for a wide extension over the earth of much warmer climates in the geological past than now obtain on the earth within moderate and high latitudes. The dawn of the modern period in geology is very nearly coincident with the promulgation of the theory of glaciation and is usually dated from the appearance of Lyell's "Principles of geology." In the first editions of this classic work Sir Charles had outlined the evidence for much warmer climates during the Carboniferous and other geological periods. To the work of Hutton and Lyell and to their exposure of the fallacies of the doctrine of "revolutions" we probably owe the great advance which marked the progress of our science in their day, for these cataclysms were conceived to have punctuated the past history of the earth and to have ushered in each new geological period in its turn. Because the theory of uniformitarianism which replaced that of cataclysms was born in controversy, the pendulum of thought swung far past the point to which it must eventually come to rest. "The present is the key to the past" meant that the laws which control changes on the earth today have remained invariably the same throughout the past ages. Yet in adopting this slogan geologists were prone to make of the present a yardstick with which to survey the past with respect to rates as well as to the nature of changes.

Man and Climate

It has been only within the present generation that the fraternity of geologists have generally awakened to the fact that man's place in the geological column has been restricted to a brief and extremely abnormal period of the earth's history, such as has supervened but once in geological history since the pre-Cambrian. Hence the attempt to use the scales derived from the present for a measure of past changes has so often led to misconception and error. Today we are living in the waning part of the Wisconsin stage of the Quaternary glacial period, the later of the two periods of widespread or continental glaciation since life first appeared on the globe.

Advance in the Knowledge of past Climates

The great advance in the knowledge of past climates made during the middle third of the nineteenth century—between the promulgation of the theory of Pleistocene glaciation, nearly coincident with the appearance of Lyell's "Principles," and the last edition of that masterpiece, in 1872—is strikingly brought out by Lyell's complete rewriting for the last edition of his chapter on climates and by the addition of an entirely new chapter, in order to include the new evidence. Attention is focused

on the warm climate inferred from the fossils of the chalk, on the abundance and the variety of reptiles in the Oolite and Lias formations, and on the wide distribution of the fossil plants, shells, corals, and reptiles in the Carboniferous period.

In concluding these chapters, Lyell wrote:

"The result, then, of our examination . . . as to the state of the climate of former geological periods is in favor of the opinion that the heat was generally in excess of what it now is. There have been oscillations of temperature, and at least one period of excessive cold of comparatively modern date. In the greater part of the Miocene and preceding Eocene epochs the fauna and flora of central Europe were subtropical, and a vegetation resembling that now seen in northern Europe extended into the Arctic regions as far as they have yet been explored, and probably reached the pole itself. In the Secondary, or Mesozoic, ages, the predominance of reptile life and the general character of the fossil types of that great class of vertebrata indicate a warm climate and an absence of frost between the 40th parallel of latitude and the poles, a large ichthyosaurus having been found in latitude 77° 16′ N."[2]

The Tertiary climates over a wide range of latitudes were examined with great thoroughness by the Swiss savant, Oswald Heer,[3] and later by Seward.[4] Heer succeeded in estimating roughly the mean annual temperatures for each division of the Tertiary, finding that the Upper Oligocene was 16 degrees Fahrenheit higher than at present and the Upper Miocene 12 degrees Fahrenheit higher.

In 1879 there appeared an outstanding work on past climates from the pen of the Marquis of Saporta, entitled "The plant world before the appearance of man," this volume being in reality a résumé of many monographs issued earlier and now brought together in a comprehensive survey of the subject.[5] Saporta emphasizes particularly the evidence for a uniformity of climate in the past over the greater part of the globe and the general absence of climatic zones such as we have at present. He makes large use of Heer's study of the Tertiary climates. In summing up, he wrote:

"From all the facts, and notably from the investigation of the best-known fossil plants, we derive the general occurrence of a uniform but not excessive heat, which extended over the entire earth during the older periods, and the continuance of the elevation of temperature throughout many organic transformations and innumerable variations in detail" (page 139).

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[2] Principles of Geology, 11th edition, 1872, p. 231.

[3] O. Heer. Flora tertiaria Helveticæ, Winterthur, 1855-59; Flora fossilis Arctica, Zürich, 1868-83.

[4] A. C. Seward: Fossil plants as tests of climate, London, 1892, p. 151, especially chapter vi.

[5] Gaston von Saporta: Die Pflanzenwelt vor dem Erscheinen des Menschen. Translated by Carl Vogt from the French edition of 1879, 1881, p. 397, pls. 13, figs. 118.

Writing in 1890, Dr. Neumayer added his testimony concerning past climates in the following words:[6]

"On the whole, we are inclined to infer that, with the exception of the Pleistocene fauna and flora, the animal and plant remains of past ages, in their generality, point to a warmer climate than that which we now experience, and in point of fact several very striking items of evidence lead to that conclusion. The most important is the very great extension of reef-building corals in the older deposits, while their modern representatives are restricted to the warmer seas."

The first important extension of our observational knowledge of fossil floras within the Antarctic region came with the five synchronous Antarctic expeditions which went out in the opening years of the new century. The Swedish expedition, under Otto Nordenskjöld, brought back many examples of plants of Jurassic age, including ferns, cycads, and conifers, all indicating a mild and moist climate.* The British expedition of the same period, under Scott, discovered in South Victoria Land the Beacon sandstone with an included coal seam containing a fossil conifer, and this same formation was found later by the first Shackelton expedition of 1907-1909 in latitude 80 degrees south, or only ten degrees from the South Pole.

A new and very important advance was made in our knowledge of past climates when it was discovered, near the close of the nineteenth century, that a widely extended continental glaciation had occurred, mainly in the Southern Hemisphere, within the Permo-Carboniferous period. Evidence for local glaciation within the Northern Hemisphere about this time had been discovered by Ramsay in England as long ago as 1855, and, stimulated by this discovery, the Blanfords, only four years later, found evidence of ice action in the Talchir beds of Hindustan. Similar evidence of ice action was discovered by A. R. C. Selwyn in the same year in Australia, and the first reports of similar ice action were discovered in South Africa in 1870, and a suggestion of the same from South America in 1889. It was not, however, until the early years of the present century that sufficient evidence from these areas had been collected to prove a widely extended glaciation for the Southern Hemisphere.[7] Confirmation of Derby's suggestion concerning

* T. G. Halle: The Mesozoic flora of Graham Land, Svenska Sydpol pp. 1901-03, vol. 3, Geol., Paleont., pp. 1-121, pls. 1-9.

[6] The climates of past ages. Nature, June 12, 1890, p. 149.

[7] T. W. Edgeworth David: Evidence of glacial action in Carboniferous and Hawksbury Series, New South Wales. Quart. Journ. Geol. Soc., vol. 43, 1887, pp. 190-196; R. D. Oldham, ibid., vol. 50, 1894, pp. 463-671; A. W. Rogers: Glacial conglomerate in Table Mountain Series. Trans. So. Afric. Phil. Soc., vol. 16 (1905-7), 1907, pp. 1-8.

the Brazilian region was delayed until 1906, when abundant evidence was brought forward by both I. C. White and David White.[8]

Effect of Glaciation on the Life of Delicate Organisms

With two periods of continental glaciation, each of which occurred as brief interruptions to the normal condition at other times, the time was ripe for reaching a generalization concerning the effect of continental glaciers on the life of delicate organisms. A general survey of the effect of the Permo-Carboniferous with regard to plants was brought out by David White in 1907.[9] His conclusions were that the cosmopolitan or world-wide floras, which indicate equability of climate, occurred in various parts of the southern land areas up to some point in the Upper Coal Measures, or Upper Stephanian; but that these floras became replaced at the base of the Brazilian Coal Measures by the Gangmopterus flora, fitted to withstand colder climatic conditions. The Gangmopterus flora follows immediately the horizon of the glacial deposits here as well as in India, Australia, and South Africa. This cold-climate flora is followed by immigration of a few of the hardier types from the northern cosmopolitan flora, then by northern pteridophytic types and gymnospermous trees without annual rings, thus indicating the restoration of an equable Permian climate.

Three years later David White and F. H. Knowlton, in a paper read before the Washington Acadamy of Sciences, formulated the first general statement concerning the relation of past climates to periods of abnormal temperature, such as extensive glaciation, and in this paper they stressed the general absence throughout geological history of climatic zones.[10] After an interval of nine years Knowlton treated the subject with greater fullness.[11]

The conclusions expressed in this joint paper by two of our most eminent paleobotanists are in language difficult to improve for terseness and simplicity, and I shall take the liberty of citing with some fullness:

"1. Relative uniformity, mildness (probably subtropical in degree), and comparative equability of climate, accompanied by a high humidity, have

[8] I. C. White: Geology of Brazil. Science, vol. 24, 1906, pp. 377-379; David White: Journ. Geol., vol. 15, 1907, pp. 615-633.

[9] Permo-Carboniferous Climatic Changes in South America, Journ. Geol., vol. 15, 1907, pp. 615-633.

[10] David White and F. H. Knowlton: Evidences of paleobotany as to geological climate. Science, vol. 31, 1910, p. 760

[11] F. H. Knowlton: Evolution of geological climates. Bull. Geol. Soc. Amer., vol. 30, 1919, pp. 499-566.

prevailed over the greater part of the earth, extending to, or into, the polar circles, during the greater part of geologic time since, at latest, the Middle Paleozoic. This is the regular, the ordinary, the normal condition. From a broad point of view these conditions are relatively stable.

"2. The development of strongly marked climatic zones, at least between the polar circles, is exceptional and abnormal. It is usually confined to short intervals, or to intermittently oscillating short intervals, all within relatively short periods.

"3. The periods of abnormal climatic differentiation are characterized by the development of extremes—*i. e.*, by extreme and abnormal heat or cold (glaciation), humidity, or aridity, which are local or regional in their occurrence and variable or unstable.

"4. The brief geological period in which we live is a part of one of the most strongly developed and unstable of these abnormal intervals of radical change. The assumption that climatic variations, contrasting extremes, and complexity of combination and geographic distribution of climatic factors, such as now exist, are normal or essential, and that they were present also, though in slightly less degree, in all geological periods, appears to be without paleobotanical warrant. The proposition that we are still in the glacial epoch is paleontologically true. We have no evidence that in any other post-Silurian period, with perhaps the exception of the Permo-Carboniferous Glacial period, have the climatic distribution and segregation of life been so highly differentiated and complicated as in post-Tertiary time.

"5. The development and existence of torridity—*i. e.*, of a torrid zone in the equatorial belt or any other great region of the earth—is concomitant and causally connected with the development of regional frost. It would appear that the occurrence of a torrid zone is peculiar to abnormal or glacial intervals."

In his later monograph Knowlton states:

"It is perhaps not too much to say that it has now been demonstrated beyond reasonable question that climate zoning such as we have had since the beginning of the Pleistocene did not obtain in the geologic ages prior to the Pleistocene. I think this statement of conditions is very generally accepted by geologists and paleontologists—in fact, I am at a loss to know how the data available can be otherwise interpreted" (pages 537-538).

Causes of continental Glaciation

But what were the conditions within the seas during the greater part of geological history? Schuchert, after completing a comprehensive study of the life of these seas, wrote in 1914:[12]

"The marine 'life thermometer' indicates vast stretches of time of mild to warm and equable temperatures, with but slight zonal differences between the equator and the poles. The great bulk of marine fossils are those of the shallow seas, and the evolutionary changes recorded in these 'medals of

[12] Charles Schuchert: Climates of geologic time. Smith. Rept., 1914, pp. 277-311.

creation' are slight throughout vast lengths of time that are punctuated by short but decisive periods of cooled waters and great mortality, followed by quick evolution and the rise of new stocks. . . . On the land the story of the climatic changes is different, but in general the equability of the temperature simulates that of the oceanic areas. In other words, the lands also had long-enduring times of mild to warm climates."

As regards the causes of the great continental glaciations which have brought about such profound changes within the earth's atmospheric circulation, it is perhaps sufficient to say that of the many theories which have been promulgated none have succeeded in convincing a very large body of geologists of their competency to explain the facts. Many have passed into the limbo of abandoned theories.

Mechanics of Process of Changes produced by continental Glaciers

Though unable to find the cause of glaciation, we may with greater confidence examine the mechanics of the process through which a continental glacier brings about changes in the atmospheric circulation and so brings into existence a zonal distribution of climates, such as existed in the Permo-Carboniferous and post-Tertiary periods. As in arriving at correct notions concerning the nature of past climates it was first essential to get rid of erroneous theories which have suggested the course of investigation, so now, in dealing with the mechanics of the process by which a continental glacier exerts its influence on the atmosphere, it has been necessary to dispense with the prevalent but erroneous idea of polar calms, polar low pressure areas, and circumpolar whirls, as these were envisioned by William Ferrel at a time when exploration had but touched the edge of the earth's polar regions.[13] This theory drew attention away from the fact that our earth's geographic poles, instead of being similar, are of opposite types. One, the northern, is surrounded by a deep ocean basin largely covered over throughout the year by a complex of ice floes, while the region surrounding the other pole, the southern, is overwhelmed by the greater of the two existing continental glaciers with an area nearly as large as that of the United States. The other continental glacier, of approximately the size of that portion of the United States which is east of the Mississippi River, lies over Greenland and is centered about 19 degrees away from the northern geographic pole.

[13] W. H. Hobbs: The Ferrel doctrine of polar calms and its disproof in recent observations. Proc. Second Pan-American Scientific Congress, Washington, 1915-1916, Astron. Met. Seis. Sec., pp. 1-9.

To learn in what way the continental glaciers of the Pleistocene and the Permo-Carboniferous affected the atmospheric circulation, and so induced the zonal distribution of climate, we should study the rôle of existing continental glaciers in the present-day atmospheric circulation.

Effective exploration of the Antarctic region began near the commencement of the present century, but with at first very slight study of the continental glacier. Due to an abiding faith in the Ferrel doctrine of polar low pressure areas, the meteorological studies which were carried out were almost throughout directed from stations located outside the glacier itself. The Australasian expedition of 1911-1914, which was directed by Mawson, and the studies by Barkow in connection with the second German expedition to the Antarctic, directed by Filchner, are exceptions to this rule.

Studies of the Greenland continental glacier, on the other hand, began more than a decade earlier and penetrated much farther into the interior. The remarkable peculiarities of its surface winds were correctly described by Peary in 1898.[14]

In Peary's own words:

"Except during atmospheric disturbances of exceptional magnitude, which cause storms to sweep across the country against all ordinary rules, the direction of the wind of the 'great ice' of Greenland is invariably radial from the center outward, normal to the nearest part of the coastland ribbon. So steady is this wind and so closely does it adhere to this normal course that I can liken it only to the flow of a sheet of water descending the slopes from the central interior to the coast. The direction of the nearest land is always easily determinable in this way. The neighborhood of great fjords is always indicated by a change in the wind's direction, and the crossing of a divide by an area of calm or variable winds, followed by winds in the opposite direction, independent of any indications of the barometer."

This statement by Peary was the starting point of the writer's inquiries into the nature of the air circulation above continental glaciers—a study which has now extended over many years. Peary's great discovery was that of the pioneer. He did not inquire into the mechanism of the process or note the deviation from down-slope direction which is due to earth rotation. He did not consider what must be the air movements toward the interior of the continent or how air is supplied to the central area of the glacier. He recognized, however, the important fact that vast quantities of snow are constantly moving outward from the interior region toward the margin.

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[14] Geog. Jour., vol. 11, 1898, pp. 233-234.

It remained, then, first of all, to examine carefully the narratives of all other sledge travelers over inland ice, whether of Greenland or the Antarctic, as well as the usual scientific reports of their expeditions. If Peary's law is thus found to be verified, then it becomes necessary to reconstruct the circulatory process. The writer's first treatment of this subject appeared in 1910 and 1911,[15] and was further elaborated on the basis of later acquired data in 1915 and 1926.[16] The mechanism was described as the glacial anticyclone, and it owes its character largely to the characteristic figure of the continental glacier—a flat-topped dome—this figure being apparently due primarily to the distribution of the nourishing snow by the mechanism itself, though modified by ice flow within the marginal zone. The circulatory process of the glacial anticyclone is spool-shaped and includes a centripetal movement of relatively high-level air currents which carry cirrus and other related cloud types toward the central area of the glacier. There they settle slowly to the glacier surface to deposit their moisture, which had before been locked up in the ice particles of the cirri, been transformed to vapor during the descent, and now separated out as the characteristic fine, mealy snow of the central areas. From the borders of the central areas surface currents move outward centrifugally down the slopes, as described by Peary, though deviated by earth rotation, clockwise in the Northern Hemisphere and counter-clockwise in the Southern. The alimentation of the continental glacier is therefore accomplished by air currents descending from high levels, whereas in mountain glaciers nourishment is due to air currents rising from low levels.

Meteorologists are well aware that the vigor of planetary circulation depends not alone on excessive equatorial insolation, but quite as much on low temperatures within higher latitudes. It is the difference of temperatures that determines. Moreover, every continental glacier, because of the anticyclone fixed in position above it, becomes a wind pole, a reversing area for the circulation. At the present time our planet has its northern wind pole over Greenland and its more vigorous southern wind pole over the Antarctic Continent. Minor wind poles appear

[15] W. H. Hobbs: The ice masses on and about the Antarctic Continent. Zeitsch. f. Gletscherk. vol. 5, 1910, pp. 36-122; Characteristics of the inland ice of the Arctic regions. Proc. Am. Phil. Soc., vol. 49, 1910, pp. 57-129; Characteristics of existing glaciers. Macmillan, 1911, chaps. ix and xvi, and especially the afterword; The Pleistocene glaciation of North America viewed in the light of our knowledge of existing continental glaciers. Bull. Am. Geog. Soc., vol. 43, 1911, pp. 641-659.

[16] The rôle of the glacial anticyclone in the air circulation of the globe. Proc. Am. Phil. Soc., vol. 54, 1915, pp. 185-225; The glacial anticyclones, the poles of the atmospheric circulation, with an introduction by Hugh Robert Mill. University of Michigan Studies, Sci. Ser., vol. 4, pp. 198, pls. 3, figs. 53.

to be located in the Northern Hemisphere over Northeast Land, over Spitsbergen, and probably over the northern portion of Nova Zembla and the great glacier-covered Alaskan Highland; but these areas are very much smaller and are not entirely constant in their action.

Storms of greatest energy pass out from the main wind poles, returning the air to the equator. Today the general circulation is unsymmetrical with respect to the equator of the geoid. The equator of our circulation is displaced northward about seven degrees from the geoid equator, and the main northern wind pole of Greenland by 19 degrees from the geographic pole along the meridian of 40 degrees west longitude.

During the Pleistocene period these wind poles were considerably increased in vigor through their expansion, and two other similar but larger northern poles of circulation lay over northern North America and northern Europe. The planetary circulation of that time must, therefore, have been both more complex and much more vigorous than it is today, with more strongly marked development of climatic zones. The lack of symmetry with respect to the equator of the geoid must have been pronounced, but with the displacement of the equator of circulation, at least on the Atlantic face, far toward the south instead of the north, as it is today.

It is well recognized today that the cold abysmal waters of the oceans are supplied from the great glaciers of the higher latitudes, and that these currents creep slowly toward the equator, there to rise and return nearer the surface toward their source. The cold water supply is derived not alone from the melting of the great continental glaciers and from the icebergs which they supply, but also in large measure from the millions of tons of snow which are blown off the glaciers themselves wherever their margins approach the sea. Today this is exemplified by the Greenland Glacier along Melville Bay, and in the Antarctic on practically all margins of the continental glacier which are known. It has been suggested by T. C. Chamberlin that if this supply of cold water were not kept up, as would be the case in a non-glacial period, the currents of the ocean in the abysmal levels might be reversed.[17] Losinski has computed that after ten thousand years the temperature of the abysmal layers of the ocean would lose their present cold character, due to the earth's internal heat. Such a condition would aid in bringing about that uniformity of climate and effacement of climatic zones which have characterized the greater part of the geological past.

[17] T. C. Chamberlin: On a possible reversal of deep sea circulation and its influence on geologic climates. Journ. Geol., vol. 14, 1906, pp. 363-373.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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PLEISTOCENE GLACIATIONS OF THE NORTHERN HEMISPHERE[1]

BY FRANK LEVERETT

(Read before Section E of the American Association for the Advancement of Science, December 27, 1928)

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EARLY INVESTIGATORS

As this has been announced to be a centenary year for glacial geology, a few words of explanation may be needed. The relevancy of 1928 as a centenary of glacial geology is based on the fact that two important investigations of glaciers date from the year 1828. That year marks the beginning of glacial studies by Jean de Charpentier, who with Louis Agassiz took high rank in early investigations and who led Agassiz to take up glacial studies. His most important work, "Essai sur les Glaciers," was not published until 1841, but for several years previous he had presented the results of his investigations before Swiss scientific societies. In 1828 also occurred the first publication by F. J. Hugi, a bold mountaineer, of results of his studies of Alpine glaciers, entitled "Beobachtungen in den Alphen."[2] His studies brought out many facts about the structure and condition of the snow, névé, and ice at different heights, and observations on fissures and crevasses, and the rock material carried on and in the ice. He continued studies and

[1] Manuscript received by the Secretary of the Society March 22, 1929.
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This paper forms part of the symposium on the centenary of the Glacial theory.
[2] Leonard Zeitschrift für Mineralogie. Heidelburg, 1828, pp. 81-103, 177-213.

publications for nearly 20 years, an important paper by him in 1846 being entitled "Das wesentlichste über die Gletscherfrage."

Scientific studies and publications on glaciers were begun at a much more remote time than 1828, some of which were of considerable importance. What appears to be the oldest scientific paper on glaciers was prepared by an Icelander, Theodor Vidalin, and published in 1695.[3] He explained the cause of the movement of glaciers by expansion due to freezing of water and a movement down the valley due to gravitation.[4]

Perhaps the earliest glacial investigations in the Alps were by J. J. Scheuchzer, who carried on studies there between 1702 and 1711. One of his publications, entitled "Reisebeschreibung der Schweizer Alpen," is mentioned in K. von Zittel's "History of Geology and Paleontology," as the first paper on scientific investigation in the Alps.

A treatise of four volumes on Alpine glaciers was brought out by G. S. Gruner in 1760, which gives important results of personal studies and which was regarded by De Saussure as the most extensive and thorough up to that date.

H. B. de Saussure was among the earliest students to note evidence that the Alpine glaciers had been more prominent than now. He pursued studies in the Alps between 1760 and 1764, the results of which were published in 1780, under the title "Voyages dans les Alpes." Reference is made therein (volume 2, page 269) to lateral moraines on the valley walls at levels higher than the surface of the present glaciers, and also to their extent down the valleys beyond the ends of the present glaciers. De Saussure is considered by von Zittel an ideal student, with his love of truth, accuracy of observation, and freedom from bias.

Leopold von Buch is credited with the discovery that the erratics of northern Germany came from Scandinavia. In his travels in Norway and Lapland from 1806 to 1808 he noted ledges from which the erratics were derived. He also seems to have been the first to note that the old shorelines of Scandinavia have suffered northward differential uplift, their altitude above present sealevel being greater in the northern than in the southern part of Norway.

That the glaciation of Norway had once been more extensive than now was first brought to notice by Jens Esmarch in 1824.

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[3] Dissertationcula de Montibus Islandia Chrystallines Skaltholt, July 1, 1695. Translated into Hamburgisches Magazin, Hamburg and Leipzig, 1754, pp. 9-27, 197-218.

[4] This paper is cited and reviewed by Hans Reck in an important paper on the glacial studies of the recent and ancient glacier districts of Iceland, in the Zeitschrift für Gletscherkunde, Band V, 1911, p. 241.

In 1832 A. Bernhardi, without knowledge of the studies of Venetz and Charpentier, conceived the idea that the polar ice had once extended to the southern border of the North German lowland.[5]

In 1839, Böthling, a Russian geologist, described glacial deposits in Finland and Lapland and referred the wide distribution of erratic blocks to glacial action. It is the opinion of von Zittel that this paper brought the glacial theory into favor among geologists of northern Europe, who had hitherto been skeptical of the glacial theory of the Alpine geologists. This paper antedated by only a year the visit of Louis Agassiz to Great Britain that gave an impetus to glacial investigations there and also in America.

To John Playfair apparently belongs the credit of noting evidence that the elevated shorelines of Scotland are due to an uplift of the land and not to a lowering of sealevel.[6] Playfair, in Scotland, and Venetz, in Switzerland, appear to have each at about the same time discovered that erratic blocks had suffered distant transportation, and referred the transportation to glacial extension. Playfair made his views known in 1815 and Venetz in 1816, the latter without knowledge of the former's views. In notes of a tour made in 1815 Playfair remarked "that a glacier which fills up valleys in its course, and which conveys the rocks on its surface free from attrition, is the only agent we now see capable of transporting them to such a distance without destroying that sharpness of the angles so distinctive of these masses."[7]

Venetz noted the transportation of large erratic blocks from the Alps across to the Jura Mountains—a view which was at first opposed by Charpentier on the basis of its calling for a colder climate in the past than that of the present, which seemed inconsistent with the generally accepted theory that the earth is a cooling globe. But by field studies Venetz finally won Charpentier over to his view, and Charpentier then enthusiastically carried on extensive investigations, not only of the Alps, but also of the Pyrenees. As above noted, Charpentier took up these studies in 1828. He presented a notable paper in Luzerne in 1834. But his main work, "Essai sur les Glaciers," a volume of 363 pages, appeared in 1841.

Louis Agassiz became interested through Charpentier in glacial studies in 1836 and pursued them enthusiastically for the next four years, when he brought out his notable work, "Études sur les Glaciers." These

[5] Neues Jahrbuch für Mineralogie, 1832.

[6] See "Illustrations of the Huttonian theory," by John Playfair. Edinburgh, 1802, pp. 411-457.

[7] Works, vol. 1, p. 29, quoted by Charpentier in Essai sur les Glaciers, p. 246.

volumes by Charpentier and Agassiz aroused widespread interest in the study of glacial phenomena, and investigations were carried on with much zeal, not only in Europe but also in North America, in the decade 1840 to 1850. There was, however, less interest in Germany, since von Buch, who then had great influence, did not favor the theory of the Alpine students.

The first recognition of periodicity in glaciation appears to have been by E. Collomb in 1847.[8] He noted erratic blocks in elevated cols far outside and at much higher levels than the ends of the morainic loops which are conspicuous in the bottoms of the valleys radiating from the Vosges Mountains. Evidence of two distinct drifts in the Alps was brought to notice by A. Morlot in 1854,[9] and in Wales in the same year by A. Ramsay.[10]

The presence of fossiliferous beds between sheets of glacial drift was noted by E. von der Linth near Lake Zurich, in the Alps, about 1844,[11] and plants in them were later identified by Oswald Heer to be such as require a mild climate, like that which now prevails in that region.[12]

Very little additional study of interglacial deposits or of other evidence of periodicity of glaciation was carried on, either in Europe or America, until about 1870; but from 1870 to 1900 attention was concentrated on the evidence of the complexity of the glacial history in both continents, and by the latter date was sufficiently complete to show the full series of drift sheets.

State of Investigations in Asia

The state of investigations in Asia is far less advanced than in Europe or North America. The results thus far obtained seem to indicate clearly but two glacial stages, and it remains to be determined whether the glacial history there is as complex as in Europe and North America.

Distribution of Glaciation in the Northern Hemisphere

About four million square miles, or more than half of the Pleistocene glaciation of the Northern Hemisphere, was developed on the North

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[8] "Preuves de l'existence d'anciens Glaciers dans les vallées des Vosges." E. Collomb, 1847. Considered by J. Geikie a classical work. See "The Great Ice Age," 3d edition, 1895, p. 514.

[9] Bull. Soc. Vaud Sc. Nat. vol. 4, 1854, p. 41; vol. 6. 1857, p. 101.

[10] As cited by Sir Archibald Geikie in his "Life of Sir A. C. Ramsay," p. 361.

[11] "In G. Meyer von Knonaus "Gemälde der Schweiz." Band, 1, "Der Kanton Zürich," II Auflage, St. Gallen und Bern, 1844, p. 162.

[12] Heer first published the results of his studies in 1858, and later incorporated them in his work, "Urwelt der Schweiz," 1865.

American Continent and an area half as great on the European, leaving less than one-fourth of the glaciated area for the Asiatic Continent and the parts of the African and South American continents north of the equator. The Laurentide ice-sheet, which covered the northeast part of the North American Continent, probably had a maximum extent of not less than three million square miles in the last, or Wisconsin, glacial stage, or more than 90 per cent of the entire area of Laurentide glaciation. If the Iowan is included with the Illinoian glacial stage, there was an area similar to that of the Wisconsin stage. The two earlier stages, Kansan and Nebraskan, were probably of similar extent to the Wisconsin in the area covered. They were more expanded west of the Mississippi Valley, but less extended to the east. Granting the correlation of the Iowan with the Illinoian, each of the glacial stages apparently covered more than 90 per cent of the total area embraced in the Laurentide glaciation. In the Cordilleran area of glaciation, in the western part of North America, the last glacial stage embraced much more than 90 per cent of the total area of that field. In Europe the last glaciation covered more than 90 per cent of the total glaciated area. This is true of the Alpine glaciation as well as of the northern, or Scandinavian, glaciation. It appears remarkable that in several successive and independent glacial stages the ice should have had so similar an extent.

In Asia the glaciation was largely confined to prominent mountain ranges, though the northern border of Siberia seems to have carried ice at low altitudes. The prominent ranges, from the Caucasus and mountains of Asia Minor eastward along the Tian-Schan and Himalayan ranges to the high mountains of China and northward over northeastern Siberia, carried glaciers of more or less extent. Glaciation in northern Africa was restricted to small areas in the Atlas Mountains and the prominent volcanic peaks in the Mountains of the Moon. In northern South America the glaciation was restricted to a few of the high mountains of Colombia.

Glaciation on islands was conspicuous, not only in the Arctic, but also in the North Atlantic and the North Pacific as far south as northern Japan. However, some of the Arctic archipelago north of the North American Continent may not have been glaciated. This is inferred from the fact that a considerable part of Alaska escaped glaciation. It is somewhat remarkable that a light glaciation was found by R. A. Daly to have occurred on Mauna Loa, a prominent volcanic cone in the Hawaiian Islands, in north latitude 19° 30′. It was above 3,500 meters.[13]

[13] Proc. Am. Acad. of Arts and Sciences, vol. 51, 1915, pp. 158, 167.

The initiation of glaciation in the Laurentide region of North America and also on the Scandinavian Peninsula of Europe was in the belt of greatest storm frequency of the Northern Hemisphere. In the Laurentide region it was in the elevated southern part of the Labrador Peninsula and the "Height of Land" south of Hudson Bay. In Europe it was in the high range along the western coast of Norway. The Cordilleran glaciation of western North America was developed in the humid district bordering the North Pacific. Aridity increased in passing eastward, so the glaciers had but slight extent east from the crest of the Rocky Mountains, but from these mountains westward there was a general filling with ice between the several ranges from near the line of the United States and Canada northward nearly to the Arctic. As the Arctic was approached, the glaciation became weaker because of diminished precipitation. In the western United States and also in the mountains of central and southern Europe altitude and relief above border districts seem to have been the controlling factors and the relation to storm frequency a matter of less consequence. It is found, however, that the snow-line was lower and glaciation heavier on the windward than on the leeward slopes of the mountains. In the Alps and Pyrenees it was also lower down in the more humid western section than in the less humid eastern part.

In the elevated central portion of the Asiatic Continent general aridity seems to have prevailed in the Ice Age as it does today. The Pleistocene glaciation was of slight extent beyond present glaciation. It seems to have owed its extension to a lower temperature rather than to increased precipitation, though there may have been a moderate increase. The greater extension of lakes in that region in the Ice Age was probably dependent mainly on lessened evaporation. There appears to have been only a moderate extension of ice eastward from the Ural Mountains into Asia. In the last glaciation of central Asia the snow-line, as estimated by Machatschek,[14] was only 600 to 800 meters lower than today, or much less than in the humid European districts—a feature indicating relativly high aridity. The last glaciation in northeastern Siberia seems to have been less extensive than an earlier one and to have been restricted to the mountain slopes. In the earlier one the ice extended widely over the Siberian coastal slopes.[15]

As already indicated, the ice-sheets in the successive glacial stages occupied areas with somewhat different limits, so that the entire glaciated

[14] Geographische Zeitschrift, Band 20, 1914, pp. 368-383.

[15] For a summary statement and references to the literature, see "Geology of Mongolia," by C. P. Berkey and F. K. Morris, vol. ii, 1927, pp. 382-393.

area of each of the main fields of glaciation was never completely covered in any of the glacial stages. So, also, the ice-sheet of a given glacial stage had successive phases of growth, and the whole area that it is represented to have covered was not completely covered at any one time. In the last, or Wisconsin, glacial stage in North America the Laurentide ice-sheet started on the Labrador Peninsula and the "Height of Land," south of Hudson Bay, and took a southwestward course through the lowlands now occupied by the Laurentide Great Lakes into central Illinois, in what is termed the Early Wisconsin substage or stadium. Following this the part of the ice-sheet south of Hudson Bay became dominant and a more pronounced southward movement took place. It extended into districts from central Ohio eastward that had not been covered in the earlier movement, but at the same time shrank materially in Illinois and Indiana and southwestern Ohio. It was probably at this time that the ice culminated in the district south of the Saint Lawrence Valley from New York eastward and covered mountains which in Early Wisconsin time had developed local glaciers. At this time the Kettle interlobate moraine of Wisconsin was formed. For some years this was considered a late Wisconsin limit, but it has recently come to be termed the middle Wisconsin limit, or stadium, because of the recognition of a well-defined later stadium. In this later stadium the ice-sheet became prominent in the district west and southwest of Hudson Bay, and then reached its culminating position in Iowa and the Dakotas. The eastern part at that time barely filled the Ontario, Huron, and Superior basins.

What is true of the last, or Wisconsin, stage is demonstrable to a certain extent for the Illinoian glacial stage. It had first a southwestward movement from the same district as the Early Wisconsin into western Illinois and southeastern Iowa. This was followed by a southward movement through the Lake Michigan basin over eastern Illinois and western Indiana and a marked recession of the border in western Illinois. It may have been at this time that the Illinoian ice reached its culminating position in Ohio, Pennsylvania, and New Jersey. It seems to the writer not improbable that a later phase of this glaciation is represented in the Iowan drift, and that the earlier idea that the Iowan is a distinct and later glacial stage than the Illinoian is incorrect. The earlier idea still has its advocates and the question of the place and rank of the Iowan remains unsettled.

Whether the two earlier drifts, the Kansan and Nebraskan, went through a similar growth and culmination westward is not easily de-

termined, since these drifts have very limited exposure east of the Mississippi Valley.

Turning now to Europe, it is found that the Scandinavian ice had an early movement in the last glacial stage southwest and south from Norway, which covered the North Sea and reached the coast of Great Britain. With the growth of this ice-sheet the axis of movement became shifted to the Baltic lowland and the movement across the North Sea became relatively weak. Meantime the Scottish glaciation became prominent and strong enough to encroach upon the part of the British coast in England that had been covered by the ice from Norway. It seems probable that the Scottish glaciation came largely as a result of the lowering of the temperature induced by the neighboring Scandinavian ice-sheet. The Scottish ice may have had a similar rôle in inducing glaciation in the relatively low mountains of Ireland. After the Scottish ice had filled the Irish Sea and carried shells from its bed over the Irish coast, the Irish ice developed and encroached somewhat on territory that had been covered by the Scottish ice. What is true of the last Scandinavian glaciation seems to have been the succession in earlier glacial stages, the earliest advance from Norway being southwest and south into the British Isles and into Holland, while the advance through the Baltic depression came later. In the earlier glacial stages the ice extended considerably farther southeast into Russia and Poland than in the last glacial stage. The area of outlying drift here compares favorably with that of the outlying Kansan drift of the Laurentide ice-sheet west of the Mississippi Valley.

In high latitudes the ice of the last glacial stage, both in Europe and North America, had fully as great extent as in any of the earlier stages. In North America the Laurentide ice-sheet in the Wisconsin stage extended westward nearly to the base of the Rocky Mountains in Canada and terminated at an altitude of 3,000 to 4,000 feet or more. The Scandinavian ice-sheet extended eastward 900 miles, from the center of dispersion, in Scandinavia, to the base of the Timan Mountains, in northern Russia. There probably is some significant factor of the glacial history, which determined that the glaciation of the earlier stages should extend into lower latitudes than that of the last glacial stage, that awaits interpretation. It appears that the centers of dispersion were essentially the same in all the glacial stages.

The mode of development of the Cordilleran glaciation in western North America is not well worked out, even for the last glacial stage, and very little is known as to the earlier ones. It was largely a confluence of piedmont glaciers. This also seems to have been the case with

the glaciation in Scotland, Wales, and Ireland. There seems also to have been a confluence of piedmont glaciation in the most extensive glaciation of northeastern Siberia. A similar type of glaciation probably was developed in northeastern Russia.

It is a matter of some significance, concerning the influence of planetary winds on the oceans in the Glacial epoch, to note that the southern limit of glaciation on the European side of the Atlantic is 10 to 12 degrees of latitude farther north than on the North American side, from which it may be inferred that the isotherms showed a similar difference in latitude on opposite sides of the Atlantic to what is found today. This relation shows clearly that the warm waters were driven northeastward across the North Atlantic by winds in the Pleistocene glacial stages about as they are today. While the mean annual temperature may have been a few degrees lower than now on both continents, the relative temperatures seem to have been but slightly affected.

Evidence has been presented that the main ice-sheet in the North American Continent in each of the stages of glaciation started on the elevated land east and south of Hudson Bay. There is, however, a prevalent view that an independent center, known as the Keewatin center, was developed on the low plain west of Hudson Bay. The view has also been advanced that the Keewatin ice-sheet had reached large dimensions before the ice on the elevated district east and south of Hudson Bay had reached great size. In the light of present knowledge, however, it is necessary to reject the latter view and probably to so modify the interpretation of the Keewatin center as to restrict it to a closing phase of ice radiation. In this closing phase a part of the Laurentide ice-sheet may have persisted about as long on the west side of Hudson Bay as on the Labrador Peninsula. On this peninsula, as shown by Low,[16] the center of ice dispersion migrated northward from about latitude 50 degrees to latitude 55 degrees in the course of the waning of the last stage of glaciation.

Comparison of the Snow-line of the last glacial Stage with the present Snow-line

Two important papers on this subject, published in the *Zeitschrift für Gletscherkunde,* have summarized the relation between the Ice Age and present snow-lines in various glaciated areas. They pertain chiefly to the mountain glaciations, because the areas covered by the great ice-sheets are almost entirely below the level of the present snow-line. The earlier paper, by Fritz Machatschek, appears in volume 8, 1913. A

[16] A. P. Low: Geol. Survey of Canada, Ann. Rept., new series, vol. 13, 1900, p. 81D.

later paper, by Fritz Klute, appears in volume 16, 1928, and deals with the significance of the depression of the snow-line in Ice Age problems. It is illustrated by several profiles showing the Ice Age and present snow-lines in various parts of the earth.

Data by Klute show that the Ice Age snow-line on the Rocky Mountains in latitude 45 degrees is 600 to 700 meters lower than the present snow-line, which is placed at 4,000 meters. In the Cascades, near the Pacific coast, the Ice Age depression is estimated to range from 1,000 to 1,400 meters and the present snow-line is placed at 3,000 meters. It thus appears that the humid district was affected to a markedly greater degree than the arid district.

Machatschek estimates the depression of the Ice Age snow-line of the Rocky Mountains in latitude 39 degrees to be 1,000 meters lower than the present, which is put at 4,300 meters. In the Wasatch Mountains, in latitude 40 to 41 degrees, the western slope shows 1,000 meters depression of the snow-line, while the eastern, more arid slope shows only 700 meters. The present snow-line is put at 3,500 meters.

Klute estimates the Ice Age depression on Mount Whitney, in the Sierra Nevada, latitude 36° 40′, to be 1,000 meters and the present snow-line 4,200 meters. Machatschek estimates the depression of the snow-line on the arid east slope of the Sierra Nevada to be only 650 meters below the present snow-line, which is put at 3,650 meters.

The snow-line in Scandinavia is estimated by Klute to have been depressed in the Ice Age at least 1,000 meters below the present snow-line. In the Alps the depression in the Ice Age is estimated by Machatschek to range from 900 meters in the drier parts to 1,300 or 1,400 meters in the most humid parts. Klute, however, estimates a depression of only 800 meters in the central Alps. In the Pyrenees, Machatschek estimates the humid western part to have had a depression of 1,200 meters (from 2,500 to 1,300 meters), while the middle part had a depression of 1,000 meters (from 2,700 to 1,700 meters) and the eastern part 900 meters (from 2,900 to 2,000 meters). As one passes south from the Pyrenees to the more arid districts, the depression of the Ice Age snow-line becomes less, being estimated by Klute to be 800 meters in the Sierra Nevada and in the Atlas Mountains. He estimates the depression in the Mountains of the Moon, in equatorial Africa, to have been only 700 to 800 meters. In the Caucasus Mountains the depression of the Ice Age snow-line is estimated by Machatschek to have been 1,300 meters in the humid western part and 900 to 1,000 meters on the north slope of the middle part, while in the interior of the mountain system it was about 700 meters.

In the Tian-Schan of central Asia the Ice Age depression is estimated by Machatschek to have been only 600 to 700 meters. In the northwest part of the Himalayas he estimated a depression of about 800 meters, while on the humid south slope it was much greater, possibly 1,600 meters. In the Chinese and also in the Russian parts of the Altai Mountains he estimates a depression of 800 to 900 meters. Klute estimates an Ice Age depression of 900 to 1,000 meters in the mountains of Kamchatka and a similar depression in the mountains of the north part of Japan.

In this connection it is of interest to note that the Driftless Area of the Upper Mississippi Valley gives evidence that the Ice Age snow-line was farther north than its northern limits; otherwise this area would have been glaciated. The present annual mean temperature at the north border of the Driftless Area is only 42 degrees Fahrenheit. From this we may infer that the lowering of temperature in the Ice Age was somewhat moderate. As the Driftless Area was not overridden by ice in any of the glacial stages, the above-mentioned moderate amount of lowering applies to each of the stages. The unglaciated part of the Allegheny Plateau in southwestern New York, standing 2,000 to 2,400 feet above sealevel, was also outside the limits of the Ice Age snow-line. The great extension of the ice-sheet beyond the Great Lakes in the district lying between the Driftless Area and the Allegheny Plateau was thus an ice invasion into districts standing outside the Ice Age snow-line. The low basin now occupied by the Great Lakes gave the ice a free passage.

Evidence that the Ice Age lowering of the snow-line in the Alps was mainly due to a lowering of the temperature, and in but a minor way to higher precipitation, has been repeatedly set forth by Penck and Brückner in their publications on the Alpine glaciation. They have called attention to the fact that there was but little increase in the height of the snow filling in the higher part of the Alps in the Ice Age than the present filling. A lowering of temperature seems to be required to give rise to ice-sheets, in northeastern North America and northwestern Europe, of the dimensions reached in each of the glacial stages. It seems highly improbable that increase of precipitation could have been a leading factor. The very moderate lowering of the snow-line in the mountains of what are now relatively dry areas, as shown in the above data, seems to indicate that they were relatively dry in the Ice Age.

Evidence of warm interglacial Stages

The estimates of the warmth of the interglacial stages are based on the presence of a warm climate fauna and flora in beds lying between

glacial deposits. Estimates of the length of interglacial stages are based on the amount of weathering and erosion a given drift had suffered prior to the next succeeding glacial stage. The conditions for the preservation of remains of terrestrial animals and plants in interglacial beds are much more favorable in the early relatively cool part of an interglacial stage than in the warmer middle part, owing to the slow rate of decomposition under cool conditions; but conditions for the preservation of the remains of fresh-water and marine species are favorable under warm as well as cool climate. As a consequence, the greater part of the evidence as to the degree of warmth reached in an interglacial stage is based on the species imbedded under water. If there are found species that are now restricted to warm or temperate climates, it may be inferred with some confidence that the fossil species lived under similar climatic conditions.

The studies of the fauna and flora of interglacial beds are now sufficiently advanced both in Europe and America to bring out clear evidence that conditions at least as warm as the present were prevalent in each of the interglacial stages. In some cases, as in the beds at Toronto, Canada, there is some uncertainty as to which interglacial stage the fossiliferous beds belong; but usually the geological horizon has been determined with a fair degree of certainty. In the Alps nearly all the fossiliferous interglacial beds are referred to the last, or Riss-Würm, interglacial stage, but in northern Europe and in America they are fully as abundant in each of the earlier stages.

The beds of interglacial plants in the Alpine region are known as "Schieferkohlen" in the German literature. They seem to have attracted attention earlier than the interglacial beds associated with the deposits of the Scandinavian and North American ice-sheets. Some of the beds near the east end of Lake Zurich were brought to notice by Escher von der Linth in 1844, and the fact that the plants are of warm temperate species was first announced by Oswald Heer in 1858 and repeated in his first edition of "Urwelt der Schweiz" in 1865. A bed at Morschwyl, on the south shore of Lake Constance, was first brought to notice by F. C. Deike in 1858, and its warm temperate flora was discussed by Heer in the first edition of his "Urwelt der Schweiz." The occurrence of interglacial warm temperate plants was noted later in the "Hötting breccia," near Innsbruck, in the midst of the Alps. These plants indicate a warmer climate than the present. These beds all seem referable to the Riss-Würm, or last interglacial stage. A fossiliferous bed at Leffe, in the Serio Valley, on the south slope of the Alps, underlies gravel of the Riss glacial stage, so is at least as old as the second, or

Mindel-Riss, glacial stage. Some geologists refer it to early Pleistocene or to the Pliocene. There is no uncertainty as to the interglacial age of the other beds mentioned, for they lie between glacial deposits, and the overlying drift appears to pertain entirely to the last, or Würm, glacial stage. The Hötting flora is thought to call for a snow-line 400 meters higher than the present, and the others to require a raising of the snow-line at least 1,000 meters above that of the last glacial stage.

Passing to northern Europe, we find that its earliest glaciation was followed by a stage in which conditions of climate were fully as mild as the present. The Cyprina clays of Denmark, North Germany, and Holland, also known as the Eemian deposits, carry estuarine and marine molluscan fossils that are chiefly of species whose present habitat is somewhat farther south. Two species of *Cardium* now have their northern limit in the English Channel; one species of *Mytilus* now has its northern limit on the west coast of France and another is confined to the Mediterranean. These and others whose northern limit is now in the south part of the North Sea are all characteristic forms. The whole assemblage is thought to indicate that the present equivalent of the Eemian Sea of Denmark is to be found in or near the English Channel.

In the vicinity of Berlin borings have brought to light beds containing the fresh-water mollusk *Paludina diluviana* in such abundance as to give them the name "Paludina beds." The present habitat of this mollusk is in streams tributary to the Black Sea, so it is of decidedly warm temperate type. The beds, as in the case of the Eemian deposits, appear to fall in the first interglacial stage. They lie between the old and the oldest drift of that region.

The Cromer Forest-bed of the coast of Norfolk, in eastern England, has been found to carry no less than 68 species of plants, which have had careful study by Clement Reid and been found to indicate a climate very similar to the present. There is an absence of Arctic plants. But above the Forest-bed and below the oldest known glacial deposit of Norfolk are two beds, the first a marine bed characterized by *Leda myalis, Astarte borealis,* and other shells of Arctic type, and above this a fresh-water or flood deposit with Arctic plants—the Arctic willow, the dwarf birch, etcetera. The overlying till is thought to be referable to the second glacial stage, in which case the Cromer Forest-bed may have a similar age to the Eemian beds. It is underlain by the Weybourn crag, of marine origin. This has a fauna with much higher per cent of northern species than the beds below it, and is thought to show the influence of neighboring glaciation, such as may have then been present on the Scandinavian Peninsula.

At many places in north Germany interglacial beds carrying the remains of extinct vertebrates, as well as of both extinct and existing species of mollusks of temperate habitat and of plants, have been brought to notice by various students. The essential data down to 1909 have been summarized by Felix Wahnschaffe in the third edition of his "Die Oberflachengestaltung des norddeutschen Flachlandes." It is clearly shown that there are at least two horizons at which interglacial beds carrying fossils of temperate types are present. Similar beds have been noted over wide areas in Russia, reports of which are scattered through the Russian literature.

In North America the most comprehensive treatise on the life of the Pleistocene is a volume of 476 pages by F. C. Baker, issued as a bulletin of the University of Illinois. It lists nearly every published occurrence of interglacial beds carrying plant or animal remains and attempts to refer them to the proper horizon. In some cases the references are manifestly incorrect, but in the main they appear to be correctly placed. There are also some cases in which the horizon is in doubt.

In regard to the climatic conditions in the first, or Aftonian, interglacial stage, Baker states, on a basis of the study of the fauna and flora, that the climate was moist and the winters were not too severe for such animals as the elephant, horse, and peccary. The type of mollusks, of which 50 species have been identified, indicates a climate not essentially different from that of today. The land snails attest the presence of a rich flora. The plants include trees, such as pine, larch, spruce, elm, and poplar, all of existing species. The mollusks show some varietal differences from the existing species. Of 25 species of vertebrates, 23 are now extinct. The mammalian fauna resembles most closely the Equus zone or Sheridan formation described by Osborn.[17] The large mammals probably found refuge in the preceding glacial stage south of the ice-sheet and migrated northward as soon as the Aftonian climate became favorable.

In regard to the life of the second, or Yarmouth, interglacial stage, Baker states that, as far as the plants and mollusks are concerned, the life was very little, if any, different from that of today. Of 92 species of mollusks, only two species are extinct. That a portion of the country was dry is attested by the loess deposits and their fossils. The presence of the giant sloth, tapir, and peccary point to a warmer climate than the present. This interglacial stage is known to have been much longer than the third interglacial stage and may have exceeded the first in

[17] H. F. Osborn: Bull. 361, U. S. Geol. Survey, 1909, pp. 85-86; also, Jour. Geology, vol. 18, 1910, p. 214.

length. This is the case in the Alps and probably elsewhere in Europe, as well as in America.

There is some uncertainty as to the place of the interglacial beds at Toronto. Baker refers them provisionally to the third interglacial stage, but it seems to the present writer more probable that they are to be put in the second interglacial stage. There have been 45 species of plants identified in this deposit, three of which are extinct. Such plants as the papaw and osage orange, as well as species of maple, ash, oak, hickory, elm, and basswood, are cited by Baker as evidence of a genial climate. He thinks the Unio molluscan fauna indicates the same condition. Three species do not now live in the Saint Lawrence drainage, being confined to the Ohio and Mississippi valleys, farther south. Four species still live in Lake Erie, but not in Lake Ontario. There are other species now common in Lake Ontario and tributary streams. It is a matter of some interest to note that immediately above and adjacent to these warm-climate beds, known as the Don beds, there are deposits of stratified peaty clay, known as the Scarboro beds, carrying a cold-climate fauna and flora. In them the remains of 31 genera and 72 species of fossil insects have been identified by S. H. Scudder, all but two of which are extinct.

According to the writer's interpretation, the third interglacial stage is divisible into an early part in which peaty formation and gumbotil were formed, known as the Sangamon, which was followed by a period of loess deposition, known as the "Iowan loess," and this became moderately leached in what is termed the Peorian stage, prior to the culmination of the Early Wisconsin substage of the last glacial stage. On the Iowan drift there is, instead of peat and gumbotil, an eroded surface with a pebbly concentrate, over which a loess deposit of somewhat patchy character is found, whose relation to the "Iowan loess" is not as yet clearly determined.

The plants found in the peat and gumbotil of the Sangamon substage are largely gymnosperms, spruce and cedar being conspicuous, and seem to indicate a somewhat colder climate than the present. The Iowan loess is characterized by a molluscan fauna similar to the present fauna and changing from north to south with the present fauna. The climate may have been somewhat drier than now and it was apparently fully as warm.

The Succession of Ice Invasions

Studies in each of the large areas of glaciation have shown that there were a series of ice invasions, separated by long intervals of more or less

complete deglaciation. In each of these intervals, as already indicated, the climate became at least as mild as today. From this it seems a fair inference that the ice in these interglacial intervals had no greater extent than at present.

Evidence of four glacial stages have been found in the Alps and of at least four stages in North America. There is some division of opinion as to whether there were five glacial stages, which it is to be hoped will be cleared up in the near future. The controversy is as to relation of the Iowan drift to the third, or Illinoian, drift. No serious difference of opinion has been expressed as to the place and rank of the three other drifts.

The students of the northern European glaciation are still battling over the question whether there were any intervals of deglaciation, such as are considered established in the Alps and in North America. Those who are favorable to the view that such intervals of deglaciation occurred have in most cases been unable to differentiate clearly more than three drifts. Intense interest in the matter is shown by German, Polish, and Russian glacialists, so it is probable that the succession of ice invasions in that field will soon be satisfactorily settled.

From what has been already stated, it seems clear that a lowering of temperature rather than an increase of precipitation was the chief factor in bringing on the glacial stages. But the cause for the lowering of temperature is still a matter of wide difference of opinion and will not be entered into at this time.

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BASE MAPS OF THE WORLD[1]

BY CHESTER A. REEDS

(Read before Section E of the American Association for the advancement of Science, December 27, 1928)

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INTRODUCTION

Seven base maps of the world have recently been prepared and published by the American Museum of Natural History. These maps are primarily intended for plotting geographic and biologic data, both on the land areas of the globe and in the oceans. For this purpose several types of equal-area projections have been selected and an arrangement of continents sought, so that any undue distortion of form on one map is compensated on another.

Map-makers are always confronted with a problem impossible of solution when they are asked to represent the surface of a sphere on a flat sheet of paper. However, many devices have been invented for representing the surface of the globe on a plane. They are known as map projections. There are many world-map projections and all have serious defects. The shapes of large areas are distorted and the distances are shown at different scales on various parts of the map.

The Mercator's projection, the best-known map of the world, is most misleading in these respects. It is a good map, yet it does not give a reliable picture of the earth. Areas, scales, and distances are inaccurately or inconsistently shown. Only in theory is it possible to plot the whole globe on it, as the poles are represented by straight lines at an infinite distance on either side of the Equator.

[1] Manuscript received by the Secretary of the Society, December 21, 1929.

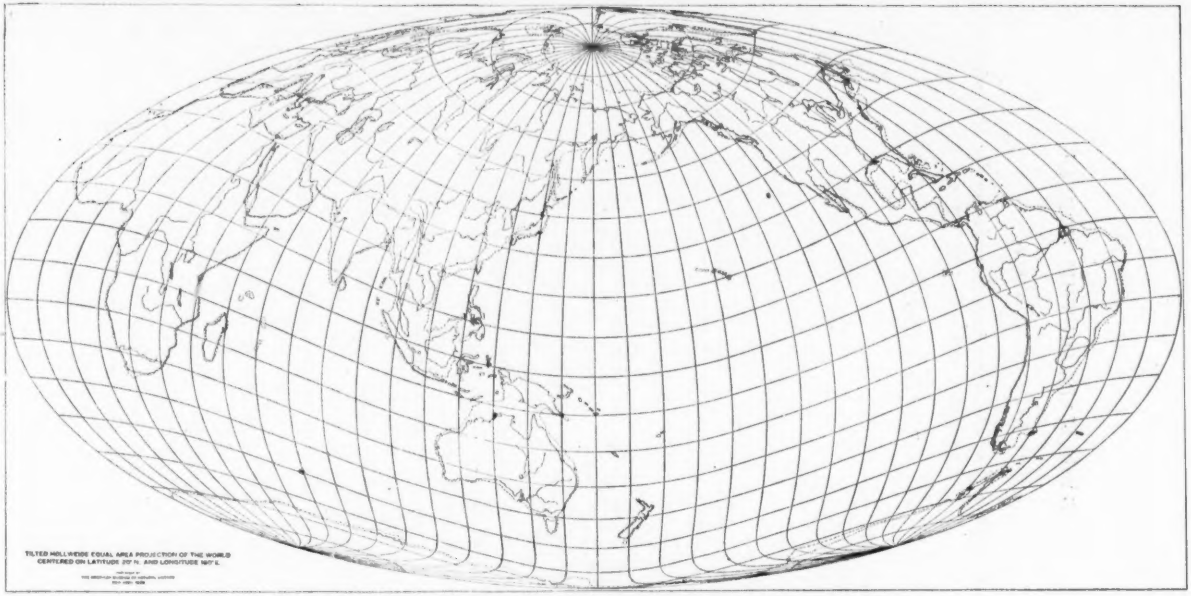

FIGURE 1 (MAP A).—*Tilted Mollweide equal area Projection of the World*

Centered on latitude 20° north and longitude 160° east. Coastal shelf areas in pale blue; oceanic depths in dark blue; lands in black and white. Original size: one meter on major axis; one-half meter on minor axis.

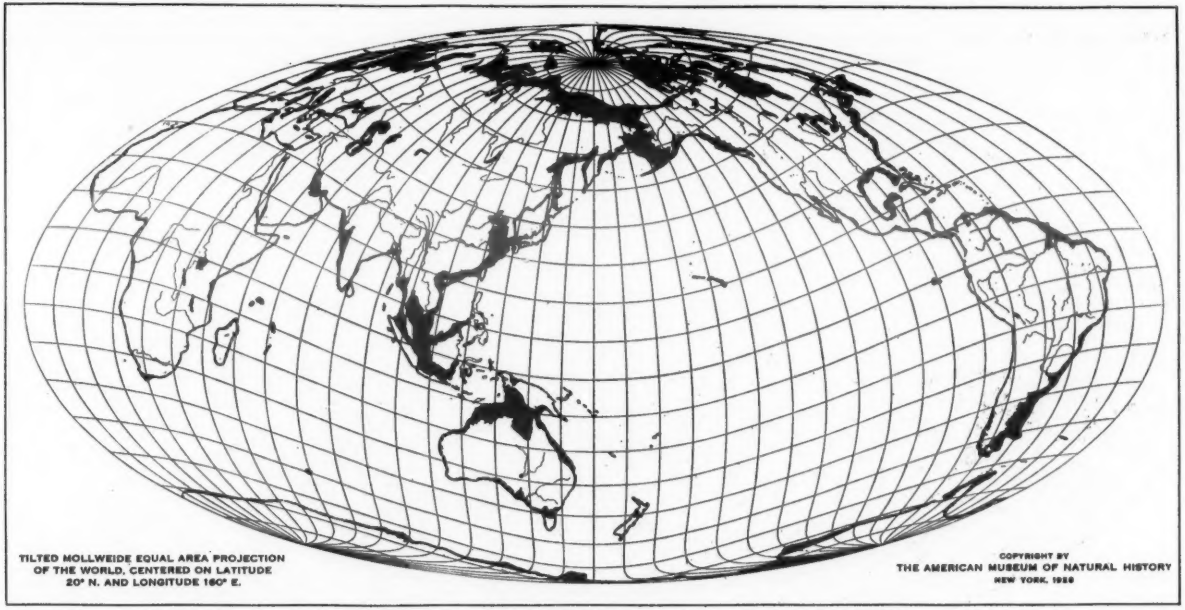
TILTED MOLLWEIDE EQUAL AREA PROJECTION
OF THE WORLD, CENTERED ON LATITUDE
20° N. AND LONGITUDE 160° E.
COPYRIGHT BY
THE AMERICAN MUSEUM OF NATURAL HISTORY
NEW YORK, 1929

FIGURE 2 (MAP A1).—*Tilted Mollweide equal area Projection of the World*

Centered on latitude 20° north and longitude 160° east. A black and white outline map with the coastal shelf areas in Ben Day. Original size: one-third meter on major axis; one-sixth of a meter on minor axis.

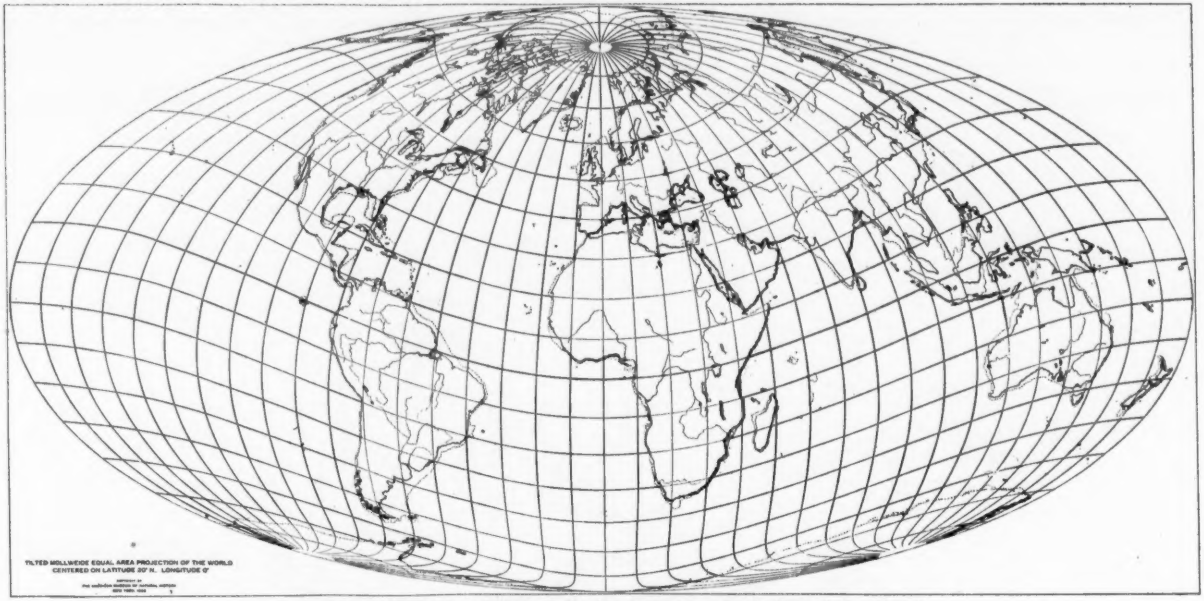

FIGURE 3 (MAP B).—*Tilted Mollweide equal area Projection of the World*

Centered on latitude 20° north and longitude 0°. Coastal shelf areas in pale blue; oceanic depths in dark blue; lands in black and white. Original size: one meter on major axis; one-half meter on minor axis.

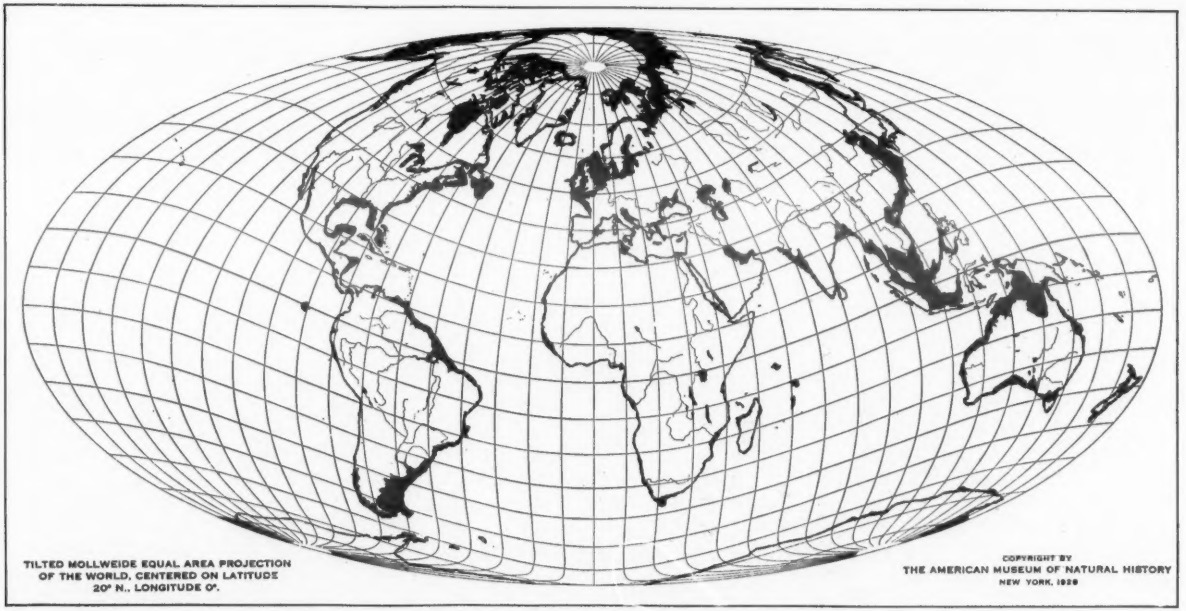
TILTED MOLLWEIDE EQUAL AREA PROJECTION
OF THE WORLD, CENTERED ON LATITUDE
20° N., LONGITUDE 0°.
COPYRIGHT BY
THE AMERICAN MUSEUM OF NATURAL HISTORY
NEW YORK, 1929

FIGURE 4 (MAP B1).—*Tilted Mollweide equal area Projection of the World*

Centered on latitude 20° north and longitude 0°. A black and white outline map with the coastal shelf areas in Ben Day. Original size: one-third of a meter on major axis; one-sixth of a meter on minor axis.

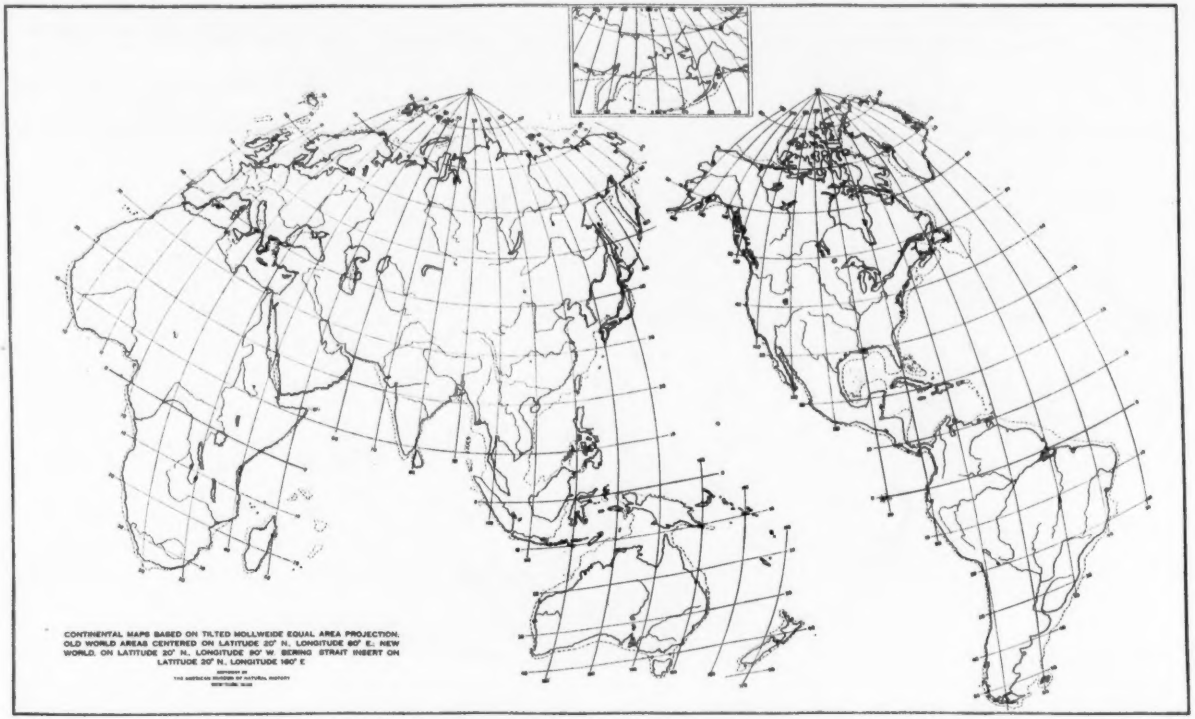
CONTINENTAL MAPS BASED ON TILTED MOLLWEIDE EQUAL AREA PROJECTION.
OLD WORLD AREAS CENTERED ON LATITUDE 20° N. LONGITUDE 80° E. NEW
WORLD, ON LATITUDE 20° N., LONGITUDE 90° W. BERING STRAIT INSERT ON
LATITUDE 20° N. LONGITUDE 160° E

FIGURE 5 (MAP C).—*Continental Maps based on tilted Mollweide equal area Projections*

Old World areas centered on latitude 20° north and longitude 80° east; New World, on latitude 20° north and longitude 90° west. Bering Strait insert on latitude 20° north and longitude 160° east. Coastal shelf areas in pale blue; oceanic depths in dark blue. The Pacific Ocean has been considerably exercised. Original size: 31.5 x 19.5 inches.

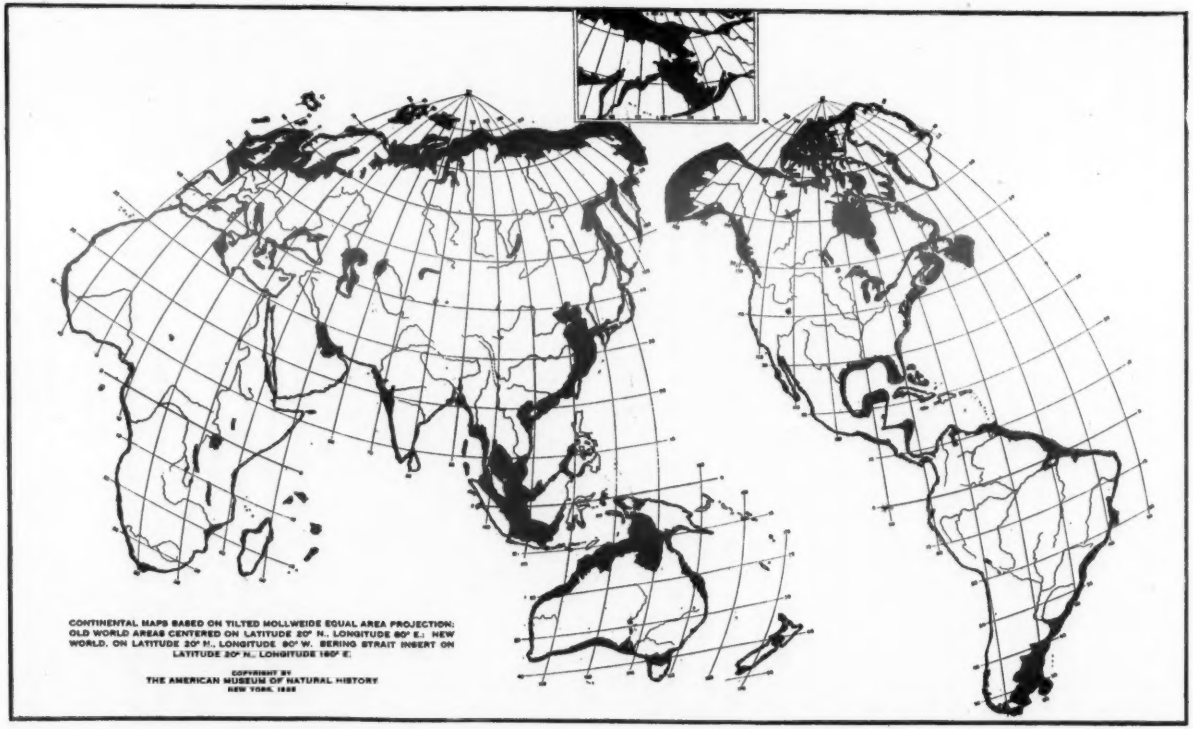
CONTINENTAL MAPS BASED ON TILTED MOLLWEIDE EQUAL AREA PROJECTION:
OLD WORLD AREAS CENTERED ON LATITUDE 20° N., LONGITUDE 80° E.; NEW
WORLD, ON LATITUDE 20° N., LONGITUDE 90° W. BERING STRAIT INSERT ON
LATITUDE 20° N., LONGITUDE 180° E.
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FIGURE 6 (MAP C1).—*Continental Maps based on tilted Mollweide equal area Projections*

A black and white outline map with the coastal shelf areas in Ben Day and the longitude and latitude specifications the same as on Map C. Original size: 15.75 x 9.75 inches.

Some of the other world-map projections possess the very valuable property of equal areas. It is important in showing distribution that relative areas be shown correctly; that shape distortion, inconsistencies of scale, and other defects be reduced to a minimum and, if possible, localized in a portion of the map that does not matter. The familiar globular projection has little merit except that it is easy to construct. Perhaps the best of this type is Lambert's zenithal equal-area projection.

Another type of world map is that which shows the whole surface of the sphere within an ellipse. In such maps the major axis is twice the length of the minor one. The best known of these is Mollweide's equal-area projection, in which the Equator is usually represented by the major axis, while the two poles are at either end of the minor axis. It is evident that, though the equal-area property may be maintained, the scale and shape in this type of projection must be considerably distorted at the edges of the ellipse.

In constructing six of the American Museum of Natural History base maps the Mollweide equal-area projection was tilted twenty degrees to the north along the minor axis. This permits an unusually clear representation of the continental areas crowded around the North Polar basin.

Maps A and A1

Maps A and A1 have been centered on longitude 160 degrees east. They show the Pacific area in nearly undistorted form, with the Old and New World continents radiating from near the center of the northern part. On these maps such data as the routes of dispersal of mammals and other organisms from a Central Asiatic point of origin eastward, westward, and southward toward the peripheral continents of Africa, Australia, and South America can be particularly well shown. From a technical point of view the projection is interesting, in that by bringing the North Pole down the minor axis twenty degrees the South Pole is split in two, each half being moved up the edge of the ellipse by a corresponding vertical amount. The resulting reduction of the Antarctic region is of slight importance for distributional world charts. The major axis on A is one meter in length, on A1 one-third of a meter. The oceans on A have been tinted blue, the continental shelves a lighter blue; the land areas have been left white. On A1 the continental shelves have been shaded in Ben Day; otherwise it is a black-and-white outline map similar to A, but only one-third the size. Figures 1 and 2.

Maps B and B1

Maps B and B1, which are complementary to A and A1, respectively, are drawn on the same grid, but they are centered on longitude 0

degrees, and therefore show the entire Atlantic and Indian oceans in nearly undistorted form. These maps are particularly useful because of the well-known faunal relationships between these two oceanic areas. The Series A and B are almost as useful for terrestrial as for marine purposes. Figures 3 and 4.

Maps C and C1

Maps C and C1 are composite maps. They have been drawn on the same projection as Series A, but they consist of three separate maps, the Old and New Worlds and Bering Strait insert, respectively, expressed in their true areal and latitudinal relationships, with a large part of the Pacific Ocean excised. The continental Old World areas have been centered on latitude 20 degress north, longitude 80 degrees east; the continental areas of the New World on latitude 20 degrees north, longitude 90 degrees west; Bering Strait insert on latitude 20 degrees north, longitude 160 degrees east. The respective continents of the Eastern and Western hemispheres have suffered, therefore, a minimum of distortion. The small insert map shows the relationship between the northeast corner of Asia and the tip of Alaska very successfully. With C 80 x 50 centimeters in length and C1 one-half the size of C, these maps should prove particularly useful for showing parallel facts of ranges and dispersal in the two Americas and the Old World. Figures 5, and 6.

Map D

Map D, a hemispherical map of the world on Lambert's equal-area projection, shows the entire Palæarctic region, as it lies about the North Pole, in true areal and positional relationships. Since it is centered on latitude 50 degrees north and 20 degrees west, it also depicts the greater part of Africa and South America. While it was designed especially for plotting glaciation in the Northern Hemisphere, it will be no less useful for expressing various other distributional facts. Figure 7.

General Comment

Maps A, B, and C are suitable for wall maps, while A1, B1, and C1, being of small size, are adaptable for class-room use and the preparation of illustrations for publication. All of these base maps have been printed on a good quality of paper, which permits of additional drafting or color-work.

The committee which prepared these maps consisted of the following individuals: A. Hamilton Rice, chairman; Weld Arnold, O. M. Miller, R. C. Murphy, G. K. Noble, Henry Fairfield Osborn, C. A. Reeds, and G. H. Sherwood.[2]

[2] For copies and prices of these maps apply to Library, The American Museum of Natural History, 77th Street and Central Park West, New York, N. Y.

FIGURE 7 (MAP D).—*A hemispherical Map of the World*

Based on Lambert's equal area projection. Centered on latitude 50° north and longitude 20° west. Oceanic waters, lakes and seas in blue; land areas in black and white. Original size: 20.25 inches in diameter.

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METHOD OF COMPUTING MECHANICAL COMPOSITION TYPES IN SEDIMENTS[1]

BY CHESTER K. WENTWORTH

(*Read before the Society December 28, 1928*)

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INTRODUCTION

By the mechanical composition of a sediment we understand the proportions of particles of different specified sizes it contains. Stated in other terms, the mechanical composition of a sediment is the frequency distribution in it of particles of different specified sizes, the frequency being measured by the weight of the particles, not by their numbers. In most natural sediments particles of about a certain specific size predominate—that is, their number is greater than that of larger or smaller particles. In some sediments this predominant or mean size represents what statisticians would call a pronounced central tendency. In certain respects the bell-shaped curve representing the frequency distribution or central tendency in the size of the particles, like many other similar curves representing physical or biological data, is closely related to the probability curve, or the so-called normal curve of error.[2]

In many sediments the deviation in the size of particles from the mean may be regarded as a result of slight fluctuations in the competence of the agent by which the particles were transported or handled, or a result of the occasional incorporation in the sediment of particles somewhat larger or smaller than those of the mean size. The variation in the sizes of the particles may therefore be regarded as due, at least in part, to

[1] Manuscript received by the Secretary of the Society February 4, 1929.

[2] F. C. Mills: Statistical methods, New York, 1924, p. 516.

errors in an approach to perfect sorting, and hence are similar to the accidental errors that are distributed according to the probability curve. In sediments of certain types there are two maximum grades of particles and two fairly well separated frequency distributions. These may be regarded as the result of two distinctly different modes of transportation and of the operation of two distinct laws of relationship, which constitute separate problems for statistical treatment.

The frequency distribution of the sizes of particles in a sedimentary deposit is a reflection of the frequency distribution of competencies depending on the velocity, density, viscosity, temperature, and other fluctuating physical properties of the air and water by which the sediments were transported, and it therefore presents a composite picture of the complex but systematic series of events involved in the formation of the deposit. Because of the variations in these physical factors and in the relations between them and the sizes of particles, the bell-shaped frequency curves may not only vary greatly in form, but may depart greatly from perfect symmetry, the departure indicating greater variation in one direction than in another. These variations in the form of the mechanical composition curve no doubt indicate differences in the conditions under which the sediments were laid down. Attempts have been made to formulate some of the differences in the mechanical composition of sediments of different origin, but the types of sediment are so numerous and the differences in composition are so subtle and so much obscured by changes in conditions that these attempts have been of little practical use.[3]

The problem is essentially mathematical and is similar to the problem of frequency distribution in general, which has been extensively studied both statistically and mathematically and for the solution of which many well established methods are available.[4] If the problem of determining the mechanical composition of sediments differs from other such problems, the difference is probably due to the smaller amount of data furnished by most single mechanical analyses and the consequent less validity of a single determination. The purpose of the present paper is to choose from the available methods those that are best adapted to

[3] J. A. Udden: Mechanical composition of clastic sediments. Bull. Geol. Soc. Am., vol. 25, 1914, pp. 730-743.

[4] F. C. Mills: Statistical methods, 1924, pp. 61-168, 516-547. See also the works cited by Mills, particularly those of Arne Fisher and Karl Pearson. The essential methods are treated in nearly all standard textbooks on statistics.

N. P. Elderton: Frequency curves and correlation (second edition). C. and E. Layton, London.

R. D. Goodrich: Straight-line plotting of skew frequency data. Amer. Soc. Civil Eng., Paper No. 1662, 1927, pp. 1-118; also in Trans. Am. Soc. C. E., vol. 91.

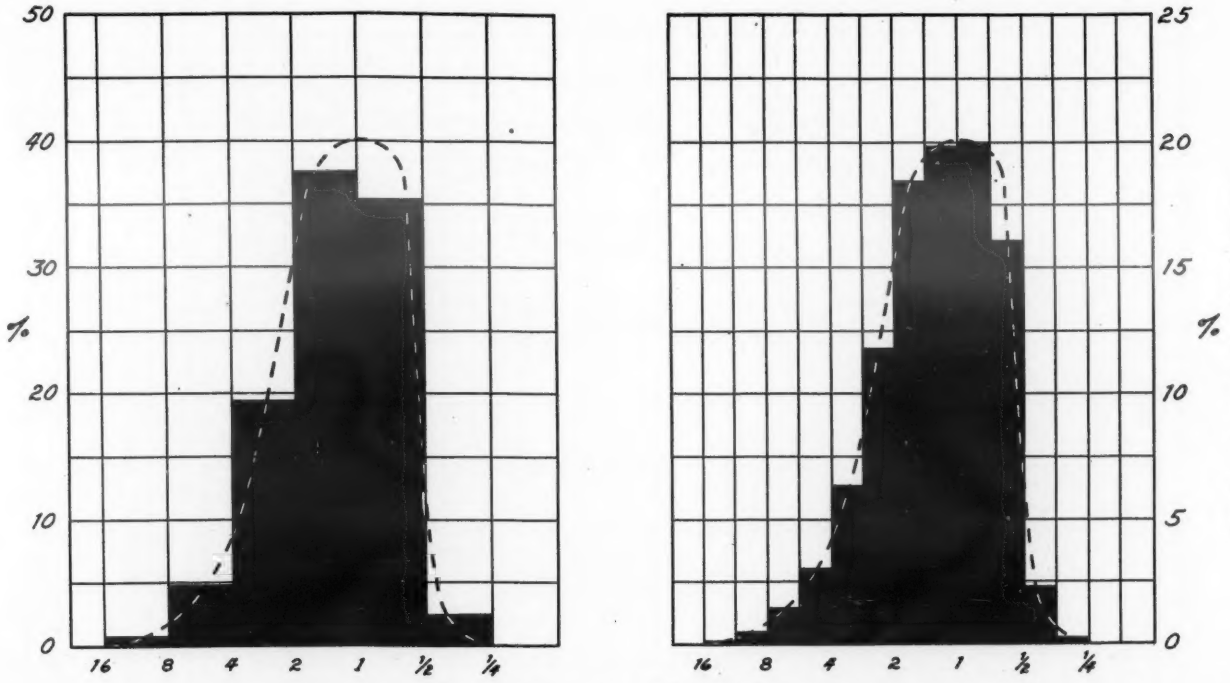

FIGURE 1.—*Diagram of the same frequency Distribution of particle Sizes*
Drawn to Ratio 2 and to Ratio $\sqrt{2}$ scales and showing the ultimate frequency curve each of these represents

deal with the somewhat meager data available, and to describe a simple method of computation that is especially adapted to the solution of the problem.

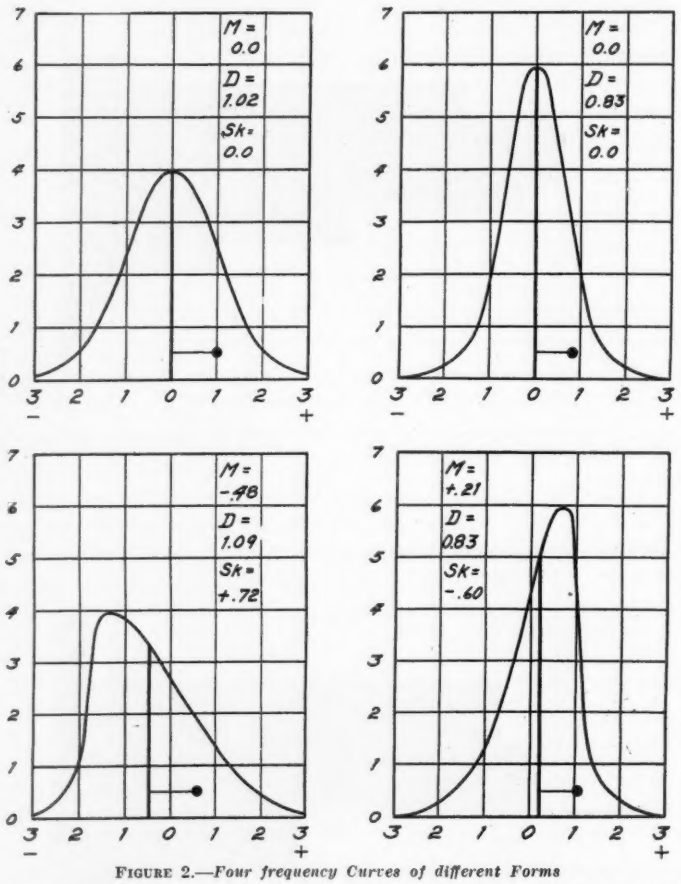

FIGURE 2.—*Four frequency Curves of different Forms*

Showing the relation between the form of the curve and the values of standard deviation and skewness. Computations were made by the methods here described, and the positive and negative integer positions correspond to the centers of the grades shown on the computing form. The large dot shows the amount of the standard deviation in each case by its distance from the heavy line of the arithmetic mean.

THE METHOD PROPOSED

Mechanical analysis of a sediment by sifting or elutriation subdivides the material into grades or classes, and the quantity of material of each

grade or class is usually determined by weighing and is computed as a percentage of the whole.[5] Plotting the percentage of these grades on appropriate coordinate forms yields a pyramidal graph, which is an approximation to the ultimate bell-shaped curve and which approaches more closely to that curve as the grades or classes become more numerous (figure 1). The problem of the investigator in this work is to deduce from the percentage data as closely as possible the characteristic form of the ultimate curve for each class of sediment and to express this form numerically (figure 2).

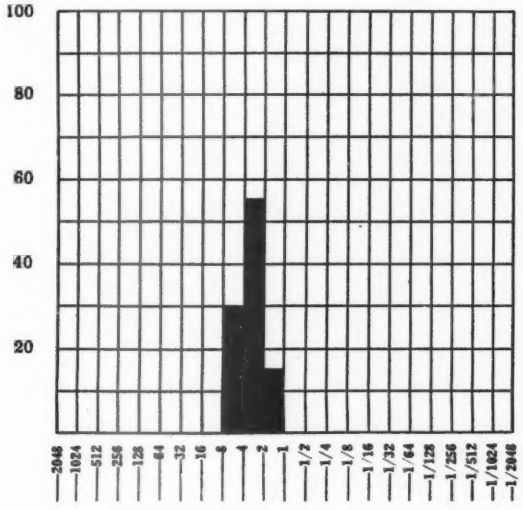

FIGURE 3.—*Standard pyramid Diagram*
Showing mechanical composition used for illustration in Tables 1, 3, and 4 (see figures 5 and 6).

In order to express the form of this curve, three elementary measures are needed. The use of more measures, such as the measure of kurtosis, or flattoppedness, is possible, but it complicates the problem. Moreover, some of the frequency distributions might be better expressed by using one of the frequency curves developed by Pearson. More extensive and more precise study of this problem may lead to the use of better methods for special purposes, but the elementary method proposed serves as a starting point in this study.

[5] J. A. Udden: Op. cit., 1914, pp. 655-744.
C. K. Wentworth: Methods of mechanical analysis. University of Iowa, Studies in Natural History, vol. xi, no. 11, pp. 3-32.

The first of the three essential measures must indicate the position of the center on the scale of sizes of particles. In working with data expressed by classes, the simple arithmetical mean is best adapted to this purpose and may be most easily computed by the method of moments from an arbitrary origin. Other measures commonly used for this purpose are the median or "halfway" position and the mode or position of the peak of greatest frequency. Neither of these can be determined directly or readily from the percentage data and neither is as useful for the present purpose as the mean. The method of computing the mean is shown in the following table, which deals with a sediment of very simple composition, made up of particles of three grades or sizes (figure 3):

TABLE 1.—*Method of Computing the Mean*

Grade	Per cent	Origin, 8-16 mm. d	$f(d)$	Origin, 2-4 mm. d'	$f(d')$
4–8 millimeters	30	1	30	− 1	−30
2–4 millimeters	55	2	110	0	00
1–2 millimeters	15	3	45	+ 1	+15
	100		185		−15
		$\frac{185}{100}=1.85$		$\frac{-15}{100}=-0.15$	

In such a computation the origin may lie either outside the limit of the data or at any point within it, but the results are invariably the same. In Table 1 the arithemetical mean is computed by taking moments about two different origins to demonstrate this fact. In the third and fourth columns the origin is taken as the center of the 8-16-millimeter grade, which is one grade smaller than the coarsest grade, represented on the customary type of graph, and hence the deviations (d) are all positive. In the fifth and sixth columns the origin is at the center of the 2-4-millimeter grade, and deviations are both positive and negative, as indicated. Deviations are multiplied by the percentage (f=frequency) to form the fourth and sixth columns, and the algebraic sum of each column divided by the total frequency of 100 represents for each grade the distance between the designated origin and the arithmetical mean or center of gravity of the system. The position of the mean computed in the two ways is identical, being—0.15 class units (that is, to the left) from the center of the 2-4=millimeter grade, which is equivalent to 0.35 unit from the 4-millimeter limit, or 1.85 units from the

center of the 8-16-millimeter grade. As each class represents the ratio 2.00, the value of 0.35 class can be found by referring to the Log_2 Table, where we find the ratio 1.275. As the mean is smaller than 4.00 millimeters, we divide by 1.275 or multiply by its reciprocal, 0.784, which is also given in the table, to obtain the approximate mean size of 3.137 millimeters. If classes smaller than ratio 2 are used, a similar procedure is employed with the logarithmic table to the proper base.

TABLE 2.—*Logarithms, Ratios, and Reciprocals to the Base 2*

Logarithm	Ratio	Reciprocal	Logarithm	Ratio	Reciprocal	Logarithm	Ratio	Reciprocal
.01	1.007	0.993	.34	1.266	0.790	.67	1.591	0.629
.02	1.014	0.986	.35	1.275	0.784	.68	1.602	0.624
.03	1.021	0.979	.36	1.283	0.779	.69	1.613	0.620
.04	1.028	0.973	.37	1.292	0.774	.70	1.624	0.616
.05	1.035	0.966	.38	1.301	0.769	.71	1.636	0.611
.06	1.042	0.960	.39	1.310	0.763	.72	1.647	0.607
.07	1.050	0.953	.40	1.319	0.758	.73	1.658	0.603
.08	1.057	0.946	.41	1.329	0.752	.74	1.670	0.599
.09	1.064	0.940	.42	1.338	0.747	.75	1.681	0.595
.10	1.072	0.933	.43	1.347	0.742	.76	1.693	0.591
.11	1.079	0.927	.44	1.356	0.737	.77	1.705	0.587
.12	1.087	0.920	.45	1.366	0.732	.78	1.716	0.583
.13	1.094	0.914	.46	1.376	0.727	.79	1.729	0.578
.14	1.102	0.907	.47	1.385	0.722	.80	1.740	0.575
.15	1.110	0.901	.48	1.395	0.717	.81	1.753	0.570
.16	1.117	0.895	.49	1.404	0.712	.82	1.765	0.567
.17	1.125	0.889	.50	1.414	0.707	.83	1.778	0.563
.18	1.133	0.883	.51	1.424	0.702	.84	1.790	0.559
.19	1.141	0.876	.52	1.434	0.697	.85	1.802	0.555
.20	1.149	0.870	.53	1.444	0.692	.86	1.815	0.551
.21	1.157	0.864	.54	1.454	0.688	.87	1.827	0.547
.22	1.165	0.858	.55	1.464	0.683	.88	1.840	0.543
.23	1.173	0.852	.56	1.474	0.678	.89	1.853	0.540
.24	1.181	0.847	.57	1.484	0.674	.90	1.866	0.536
.25	1.189	0.841	.58	1.495	0.669	.91	1.879	0.532
.26	1.198	0.835	.59	1.505	0.664	.92	1.892	0.529
.27	1.206	0.829	.60	1.516	0.660	.93	1.905	0.525
.28	1.215	0.823	.61	1.526	0.655	.94	1.918	0.521
.29	1.223	0.818	.62	1.537	0.651	.95	1.932	0.518
.30	1.231	0.812	.63	1.547	0.647	.96	1.945	0.514
.31	1.239	0.807	.64	1.558	0.642	.97	1.959	0.510
.32	1.248	0.801	.65	1.569	0.637	.98	1.972	0.506
.33	1.257	0.795	.66	1.580	0.633	.99	1.986	0.503

Having determined the mean size with reference both to the class or grade interval and to the actual diameter, we need to know the average or normal variation of sizes from this mean, or, in other words, the measure of deviation from perfect sorting. Following the reasoning both of workers in physical science and in biological or social science, we shall use the measure called the standard deviation or the root-mean-

square deviation. If the entire grouping is made up of equal units of particles, the standard diviation is the square root of the average of the squares of the deviations of the sizes of all the particles from the arithmetical mean, the computations being carried out in class-interval units and the quantities of particles being dealt with by weight expressed in percentages.

The use of equal class interval units on a fundamental logarithmic scale results in systematically changing the weighting of the data from one end to the other as compared to their treatment on an arithmetical scale. Objection has been raised to this procedure by some who have urged the use of the arithmetical scale as more natural. However, if one considers the problem of analyzing sediments having a great range of coarseness and of plotting the results in any convenient and systematic fashion, the futility of the arithmetical scale will be apparent, and it may well be asked if the logarithmic scale is not just as natural as the arithmetical. If further justification of this question is needed, it is only necessary to refer to the extensive foreign and domestic literature on "preferred numbers" for industrial and commercial measurements and to the import of the Fechner-Weber law on the various types of sense perception. As a statistical procedure, the use of arbitrary class intervals has abundant precedent, and in this problem is not only more convenient but more useful, as will be shown later.[6]

The center of gravity, or arithmetical mean, is that point about which the algebraic sum of the positive and negative first moments of all particles becomes zero. The standard deviation is based on the squares of the individual deviations and hence is based on the second moments. The arithmetical mean is the point about which the sum of all second moments is a minimum. The square root of the average of all the second moments about the mean is the standard deviation. Considered in its mechanical aspect, the standard deviation is the radius of gyration of the figure about its center of gravity, or arithmetical mean. For the problem in hand the standard deviation is computed as shown in the following table:

The squaring of the d'' values leads to a spurious accuracy and the final result is probably no more accurate beyond one place than the original figures. All the digits have been retained in the computation

[6] C. F. Hirshfeld and C. H. Berry: Size standardization by preferred numbers. Amer. Soc. Mech. Engrs. Paper read at annual meeting, December, 1922, pp. 1-32. (Discussion, pp. 32-61.)
Encyclopedia Britannica, eleventh edition, vol. 29, 1911, pp. 458-459.

above in order to show the method of treatment. The value 0.654 is a justifiable statement of standard deviation.

TABLE 3.—*Method of computing Standard Deviation*

Grade	Per cent	d''	$(d'')^2$	$f(d'')^2$
4–8 millimeters	30	− .85	.7225	21.675
2–4 millimeters	55	+ .15	.0225	1.2375
1–2 millimeters	15	+1.15	1.3225	19.8375
				42.7500

$$\sqrt{\frac{42.75}{100}} = 0.6538 = \text{standard deviation.}$$

The table shows that the diameter of the average particle as geometrically determined differs from the mean diameter of all the particles by 0.654 class or grade interval. Referring to the Log_2 Table, we find that this value corresponds to the ratio 1.573, which means that the diameter of the average particle is larger or smaller than the arithmetical mean in the ratio 1.573 to 1.000.

The third measure required in the determination of the frequency distribution curve is one which evaluates the departure from symmetry—the skewness, as this departure is called by statisticians. A number of different methods of characterizing skewness have been used and several of these have been tested in the present study. None of the measures of skewness have so rigorous or so general a mathematical justification as the other measures discussed, and choice among them must be based on the special needs in the particular problem in hand. In the study of mechanical composition the most useful formula for skewness is the one in which the skewness constant is least erratically affected by the somewhat irregular variations in the form of the block pyramid, due to slight shifts of the same fundamental curve with reference to widely spaced grade limits, and is also least subject to error where the data is confined to a very few relatively wide classes. It is highly desirable that somewhat precise characterizations of the frequency distributions for various types of sediments be developed by accurate analysis and suitable computing, but the greatest present need is for a simple and rapid procedure, which may be applied directly to the block pyramid and the precentage data by the class intervals now commonly used. It has been the writer's aim to select a measure for skewness which will best deal with the problem where the data are scanty and at the same time will be thoroughly sound in principle and capable of yield-

ing results as accurate and useful as any other measure, where the frequency curve is defined with a larger amount of data resulting from closer spacing of the sieve limits.

The results of numerous tests indicate that the measure of skewness that best meets these conditions is that based on the third moment. This measure may be described as the quotient obtained by dividing the standard deviation in class intervals into the cube root of the one-hundredth part of the algebraic sum of the cubed deviations of the diameters of all particles from the arithmetical mean. The computation of this measure is shown in Table 4:

TABLE 4.—*Methods of computing Skewness*

Grade	Per cent	d''	$(d'')^3$	$f(d'')^3$
4–8 millimeters	30	− .85	− .6141*	−18.423
2–4 millimeters	55	+ .15	+ .0034	+ .187
1–2 millimeters	15	+1.15	+1.5209	+22.813
				+ 4.577

$$\frac{\sqrt[3]{\frac{4.577}{100}}}{.654} = +.547 = \text{skewness.}$$

Thus, for the three measures the following formulas hold:

$$\text{Mean} = \frac{\Sigma(fd)}{100}$$

$$\text{Standard deviation} = \sqrt{\frac{\Sigma(fd^2)}{100}}$$

$$\text{Skewness} = \frac{\sqrt[3]{\frac{(fd^3)}{100}}}{\text{S. D.}}$$

The suggestion has been made that the mode, mean, skewness, and range of distribution be used to characterize the frequency distribution of grain sizes in sand.[7] This process involves the use of one of Pearson's

* To nearest fourth place.

[7] C. E. Van Orstrand: Jour. Wash. Acad. Sci., vol. 15, no. 2, 1925, p. 33.
C. E. Van Orstrand: Ann. Rept. Committee on Sedimentation for 1924, National Research Council, pp. 63-67, 1925.

frequency functions, for in most analyses the number of grades are too few to permit the location of the mode without the fitting of a curve. The present writer has no doubt that certain frequency distributions may be more precisely represented by functions of this sort, but he feels that for practical purposes most of them are represented with sufficient faithfulness by simple methods. Moreover, it appears that in the second paper cited the use of the arithmetical scale for plotting and computing the data derived from an analysis made with screens arranged in a logarithmic series is not only no more natural than the use of the logarithmic scale, but that such a procedure actually complicates the problem. Anyone who will plot an extensive series of analyses of sediments of various degrees of coarseness from silt to gravel to both arithmetical and logarithmic scales will perceive that plotting to the arithmetical scale is not only cumbersome, owing to the long range required, but that it produces systematic changes in the form and width of the frequency curve as one proceeds from fine to coarse sediments. This change affects both the standard deviation and the skewness, both of these measures becoming dependent to a certain extent on the position of the mean. Moreover, the skewness in turn may increase very markedly with increase in standard deviation, as is well shown in figure 2 of the second paper cited above. Here the adoption of a closer spaced scale than that used in figure 1, owing to the greater range to be covered and the consequent steepening of the fine sediment end of the curve, brings out very clearly the influence of the arithmetical plotting in introducing what the writer considers a distinctly artificial and unnecessary asymmetry. On the contrary, the plotting of skewness to the logarithmic scale shows a distribution departing only slightly from symmetry. In general the actual distribution found in a sediment plotted to the logarithmic scale shows moderate variations in skewness, ranged between nearly equal positive and negative values, as well as similar variations in sorting, and hence in standard deviation at all parts of the grade scale. For example, the best sorted beach sands and the best sorted beach gravels, though they differ greatly in coarseness, show very similar frequency distribution curves if plotted logarithmically, but radically different curves if plotted arithmetically. This condition seems to the writer more natural and more likely to permit the recognition of significant differences; and thus the logarithmic plotting and equal ratio class computing is not only justified by actually more rational.

Returning to the three constants thus far described, we find that these have been computed by the most elementary methods and the last two by direct reference to the arithmetical mean as previously determined.

Computing by this method is somewhat cumbersome because of the need for second and third powers of fractional numbers. Means have been developed by statisticians for computing these three values by reference at once to any arbitrary origin and for correcting the last two values in order to find the true values of the second and third moments with reference to the arithmetical mean. It is unnecessary in this paper to develop the formulas by which this transformation is effected, for the subject has already been well covered.[8] This method furnishes the simplest means of computing the constants of a frequency distribution, and the computing procedure here presented (figure 4) is based on it. Detailed instructions for using the form are given below.[9]

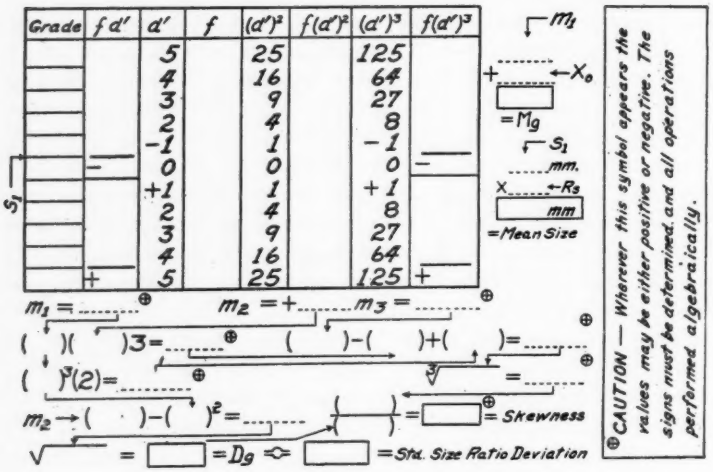

FIGURE 4.—*Blank computing Form*

For computing first, second, and third moments and the mean, standard deviation, standard size ratio deviation, and skewness based on these moments.

PROCEDURE FOR USE OF COMPUTING FORM

1. Having the mechanical analysis data in hand, select the grade nearest the center or most likely to contain the mean size and write its designation in the left-hand column, opposite the row of ciphers, and its percentage in the fourth column, under (*f*), in the same row.

[8] F. C. Mills: Statistical methods, 1924, pp. 528-546.

[9] The form may be used for the actual computations, a blank used for each analysis. The writer has a stock of these forms on 4-by-6-inch cards and can supply them at $1.00 per hundred or at corresponding rates for smaller or larger quantities. Anyone needing larger quantities can probably have them printed from a zinc block at a somewhat lower price.

2. Fill in the designations of the remainder of the grades with the coarser grades above and the finer ones below and enter the corresponding percentages to the (f) column. (For ordinary work sufficiently accurate results will be obtained by using the percentages smoothed to the nearest unit, eliminating the tenths.)

3. Multiply the (f) column values by the adjacent numbers in the (d') column, placing the results in the (fd') column with the proper signs, negative above and positive below. Add the two series and record their algebraic sum on the dotted line as equal to (m_1). This value should be pointed off two places to divide by 100 and designated as positive or negative, as the case may be.

4. Multiply the (f) values by the $(d')^2$ values to form the column $f(d')^2$ and record the total of this column, divided by 100, opposite (m_2).

5. Form column $f(d')^3$ in a similar fashion from columns (f) and $(d')^3$, obtain the positive and negative totals, and record the algebraic sum, divided by 100, opposite the symbol (m_3).

6. Carry the values of (m_1), (m_2) to the positions indicated by the arrows, solving the left-hand equations first, for the values computed from these are required in the right-hand series.

7. When the standard deviation in grade units (Dg) has been determined, the equivalent standard size ratio deviation is taken from the Log_2 Table, the (Dg) value being found in the (Log) column and the ratio deviation in the (ratio) column. If the (Dg) value is larger than 1,000, the ratio value should be multiplied by 2.0 for values between 1,000 and 2,000, by 4.0 for values between 2,000 and 3,000, and so on.

8. Record the (m_1) value at the top to the right of the table on the form. Under it write the number of grades which appear in the first column above the (S_1) arrow, plus 0.5. For example, if the form is filled to the top, there would be five such grades and the (X_0) value would be 5.50. Add the (m_1) and (X_0) values, placing the result in the rectangle as the value of (Mg), which is the position of the mean size on the grade scale measured from the upper limit of the largest grade present.

9. As the (S_1) value, record the upper grade limit of the central grade (grade opposite the ciphers) in millimeters. Under it place the (Rs) value, which is found in the reciprocal column of the Log_2 Table opposite the decimal portion of the (Mg) value derived above. Multiply these values to derive the mean size in millimeters. If the value of (m^1) is greater than 0.50, either positive or negative, so that the position of (Mg) falls outside the original central class, it will be necessary to move (S_1) so that it will express the upper limit in millimeters of the grade in which the (Mg) value actually falls.

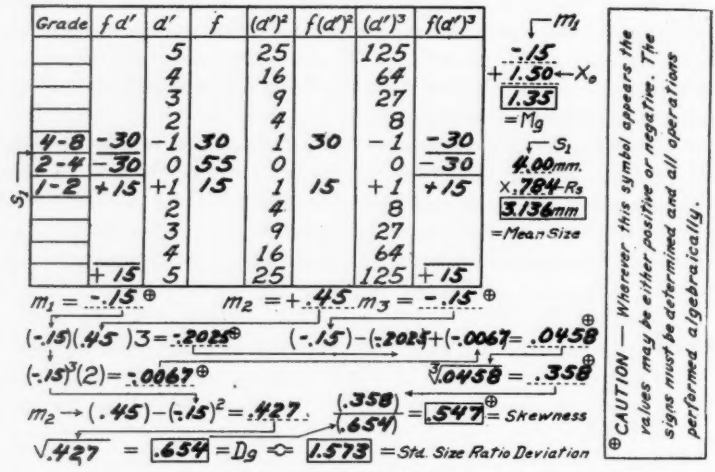

FIGURE 5.—*Computing Form*

Used in computing constants for mechanical composition of figure 3. In this case the 4-8-millimeter grade was used as the central class, avoiding the appearance of negative values. (See Tables 1, 3, and 4 and figure 6.)

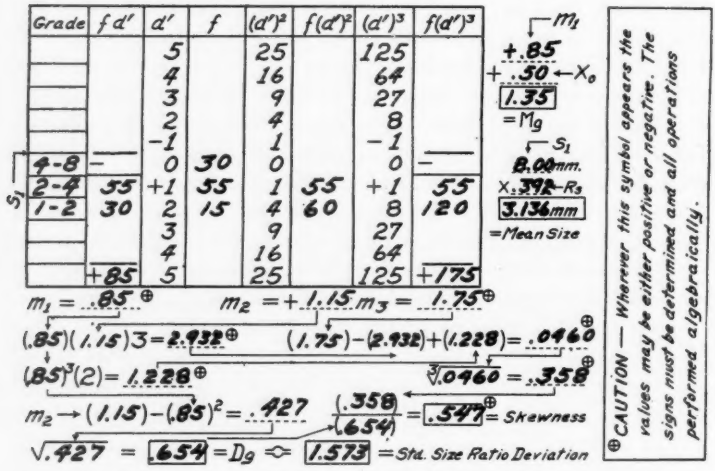

FIGURE 6.—*Form showing Computation of Constants of Analysis of Figure 3*

The 2-4-millimeter grade is used as the central class. (See figure 5 and Table 1, 3, and 4.) The agreement of the values found in figure 5 with those found here is known as the Charlier check.

The use of the form is illustrated in figures 5 and 6, in which there are computed, with reference to two different origins, the frequency measures for the problem considered in Tables 1, 3, and 4. Considerable time is saved in solving formulas and deriving roots and powers by using an 8-inch or 10-inch slide rule. In practice it is found desirable to place the grade scale so low on the form that the positive totals will always exceed the negative totals, and that the three values for the moments will be positive, and thus to avoid the chance of error in handling the negative values in the formulas. The possibility of so doing is based on the perfectly general character of the method and its independence of the position of the central grade. Hence, if the same analysis be computed twice with two different placings of the central grade, the final values for mean size, standard deviation, and skewness will be the same within the limits of accuracy of the Log_2 Table and the method of computing, provided the operations have been correctly performed. This valuable artifice for testing the correctness of one's handling of the problem is the Charlier check of statisticians.

The computing form is equally applicable to analyses made to any uniform class interval on a logarithmic scale, provided a table of logarithms to the proper base is used to make the transformations from class units to actual sizes and size ratios. For the convenience of those who wish to compute analyses made to a scale with $\sqrt{2}$ spacings, a logarithm table to the base $\sqrt{2}$ is provided below. This is used in a manner entirely similar to that for the Log_2 Table. Both tables are applicable to the Tyler standard scale based on the 200-mesh sieve, provided the proper class-limit millimeter values are used in making the transformations. It should be remembered in all these operations that the mean size, standard size ratio deviation, and skewness are universal values that are not inherently dependent on the class widths or limits used, though these may affect to a slight extent the accuracy with which these values can be determined.

Discussion and Summary

One may properly ask how accurate the values found by this method of computation will be. There is a considerable difference in this respect between the different measures. The mean size can be determined rather closely for any analysis showing subdivision in three or more classes. Standard deviation and standard size ratio deviation in such a case will be somewhat less accurate, though probably sufficiently reliable for use in placing a sediment in its approximate place. With so few classes, the

skewness value is likely to vary considerably from the true value and is probably not reliable for a single sample. The remedy is either to average the values for a number of samples thought to represent nearly identical conditions of origin or to make the analysis to a closer-spaced screen series and obtain more data. It is doubtful whether any process of

TABLE 5.—*Logarithms, Ratios, and Reciprocals to the Base—2*

Logarithm	Ratio	Reciprocal	Logarithm	Ratio	Reciprocal	Logarithm	Ratio	Reciprocal
.01	1.003	0.997	.34	1.125	0.889	.67	1.262	0.792
.02	1.007	0.993	.35	1.129	0.886	.68	1.266	0.790
.03	1.010	0.990	.36	1.133	0.883	.69	1.271	0.787
.04	1.014	0.986	.37	1.137	0.880	.70	1.275	0.784
.05	1.017	0.983	.38	1.141	0.876	.71	1.279	0.782
.06	1.021	0.979	.39	1.145	0.873	.72	1.283	0.779
.07	1.025	0.976	.40	1.145	0.870	.73	1.288	0.776
.08	1.028	0.973	.41	1.153	0.867	.74	1.292	0.774
.09	1.032	0.969	.42	1.157	0.864	.75	1.297	0.771
.10	1.035	0.966	.43	1.161	0.861	.76	1.301	0.769
.11	1.038	0.963	.44	1.165	0.858	.77	1.306	0.766
.12	1.042	0.960	.45	1.169	0.855	.78	1.310	0.763
.13	1.046	0.956	.46	1.173	0.853	.79	1.315	0.760
.14	1.050	0.952	.47	1.177	0.850	.80	1.319	0.758
.15	1.053	0.950	.48	1.181	0.847	.81	1.324	0.755
.16	1.057	0.946	.49	1.185	0.844	.82	1.329	0.752
.17	1.061	0.943	.50	1.189	0.841	.83	1.333	0.750
.18	1.064	0.940	.51	1.193	0.838	.84	1.338	0.747
.19	1.068	0.936	.52	1.198	0.835	.85	1.342	0.745
.20	1.072	0.933	.53	1.202	0.832	.86	1.347	0.742
.21	1.075	0.930	.54	1.206	0.829	.87	1.352	0.740
.22	1.079	0.927	.55	1.210	0.826	.88	1.356	0.737
.23	1.083	0.923	.56	1.215	0.823	.89	1.361	0.735
.24	1.087	0.920	.57	1.219	0.820	.90	1.366	0.732
.25	1.090	0.917	.58	1.223	0.818	.91	1.371	0.730
.26	1.094	0.914	.59	1.227	0.815	.92	1.376	0.727
.27	1.098	0.910	.60	1.231	0.812	.93	1.380	0.725
.28	1.102	0.907	.61	1.235	0.810	.94	1.385	0.722
.29	1.106	0.904	.62	1.239	0.807	.95	1.390	0.720
.30	1.110	0.900	.63	1.244	0.804	.96	1.395	0.717
.31	1.113	0.898	.64	1.248	0.801	.97	1.400	0.715
.32	1.117	0.895	.65	1.253	0.798	.98	1.404	0.712
.33	1.121	0.892	.66	1.257	0.796	.99	1.409	0.710

graphic construction or smoothing will obtain any more reliable results from a three class analysis than the computing scheme presented here. Analyses showing five or more classes will probably yield sufficiently close values of all the measures for ordinary work, and it is thought that an extended use of this computing scheme will demonstrate the need of choosing the $\sqrt{2}$ sieve scale for the well-sorted materials falling into less than five of the ratio 2 classes. However, exploration of the whole field that is opened to students by the application of statistical methods

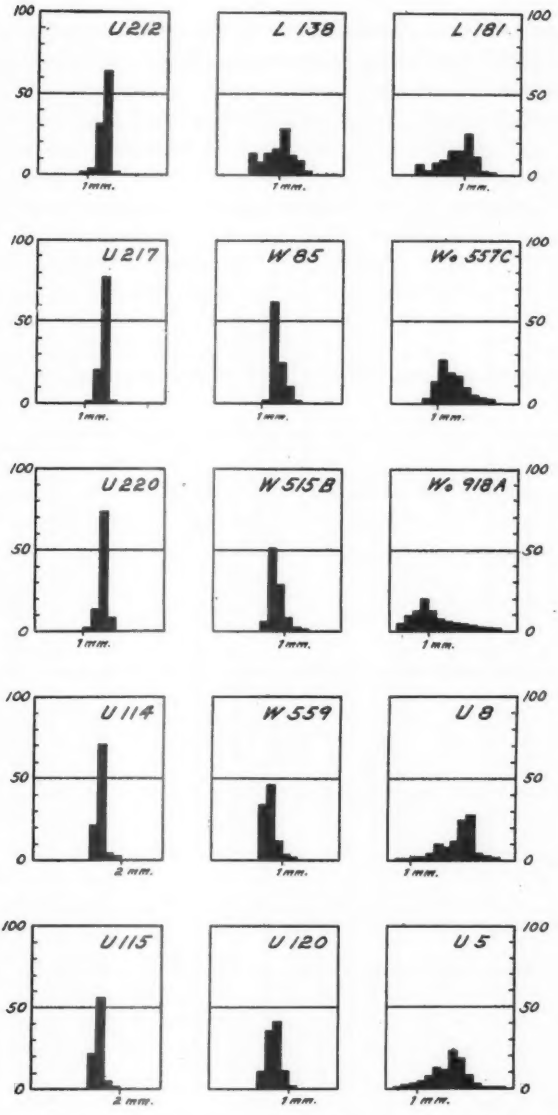

FIGURE 7.—*Mechanical Composition Pyramids of Representative Sediments of different Types*

See Table 6 for key to numbers and for statistical indices. The latter are plotted in figure 8.

to studies of mechanical composition will require the attention of many workers, and will involve the elaboration by them of additional methods and conventional treatments adapted to particular purposes.

In order to illustrate the diversity of mean size, standard size ratio deviation, and skewness values attendant on differences in the form of mechanical composition pyramids, the constants of a number of such pyramids, shown in figure 7, have been computed and are given in

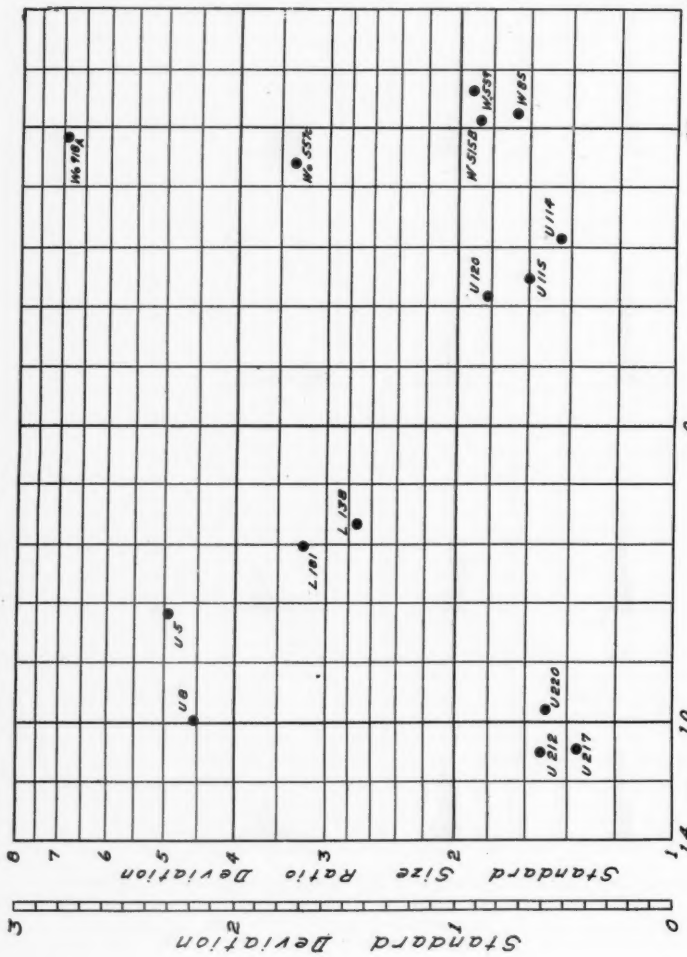

FIGURE 8.—*Chart showing Distribution of Deviation and Skewness Values for Types of Sediments shown in Table 6 and Figure 7*

Both standard deviation and standard size ratio deviation scales are shown at the left, the latter being perfectly general and independent of the computation class interval. The grouping of like sediments and the fairly distinct separation of the several groups is apparent.

Table 6. The relative positions of these values are shown in figure 8, where the size ratio deviations have been plotted against the skewness values.

In showing the positions assumed by two or three analyses of each of several types of sediments, it is not the intent of the writer to generalize on the frequency characteristics of these types, for an extended series of analyses of carefully selected sediments will be required before any broad pronouncement can be made. It is probable, moreover, that such studies will show considerable overlap between types, and that certain types may prove to be erratic and not to be classifiable with finality by this means alone.

On the other hand, it is evident that certain ranges of the several constants are likely to be characteristic of sediments of a common origin.

TABLE 6.—*Frequency Constants for Selected Sediments*

Type of sediment	Analysis number	Mean size (millimeters)	Ratio deviation	Skewness
River gravel	Lugn, 181*	1.464	3.25	− .403
River gravel	Lugn, 138*	.920	2.73	− .332
Marine lagoon?	Woodford, †557C	.330	3.38	+ .874
Marine breccia	Woodford, †918A	.595	6.92	+ .971
Till	Udden, 5	.066	4.96	− .635
Till	Udden, 8	.035	4.53	− .995
Dune sand	Udden, 212	.232	1.53	−1.097
Dune sand	Udden, 217	.206	1.37	−1.091
Dune sand	Udden, 220	.191	1.50	− .957
Volcanic ash	Wentworth, 85	.251	1.67	+1.047
Volcanic ash	Wentworth, 515B	2.000	1.87	+1.022
Volcanic ash	Wentworth, 559	2.950	1.191	+1.131
Beach gravel	Udden, 114	12.53	1.45	+ .615
Beach gravel	Udden, 115	10.84	1.60	+ .497
Beach gravel	Udden, 120	3.87	1.82	+ .429

In a study of waterlaid sediments which show a great range in the size of particles, and in which the finer particles are governed in settling essentially by Stokes' Law and the coarser particles essentially by the so-called Sixth Power Law, it is probable that the size ratio deviations and the skewness values of the coarse sediments will differ considerably from those of the finer materials. Similar dimensional effects will probably be recognized as a result of density of minerals, shapes of particles, temperature and viscosity of fluids, and other physical factors.

* These data apply only to the principal pyramid, exclusive of the coarsest grade in each case.

† The constants of the Woodford analyses are based on transformed class data rather than on the original data obtained by him.

It is evident that the frequency curve of particle sizes is really a composite function, generally based on the frequency curves of some of the variables mentioned, these being related in numerous and not always simple ways to the particle sizes. If the dependent variable were related in an exponential or other non-linear fashion to the independent variable, a strictly symmetrical variation of an independent variable, according to the probability curve, might produce a decidedly unsymmetrical distribution of values of the dependent variable. This effect and its possibilities have been briefly considered by Rietz,[10] but the writer knows of no extensive or adequate treatment of this mathematical problem. Its importance in this connection is evident.

There is a broad field for present and future investigation by students of this general problem, for which some rational standard mathematical method of determination is absolutely essential. Future studies will, no doubt, bring refinements and generalizations of great importance. The method here described embodies some of the principles of mathematical statistics in a form convenient for the use of geologists. More rigorous treatment of the subject will in time be required.

[10] H. L. Rietz: Mathematical statistics, 1927, pp. 72-75.

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AGES AND DIFFERENTIATION SERIES OF THE BATHOLITHS NEAR THE MINNESOTA-ONTARIO BOUNDARY*

BY FRANK F. GROUT

(*Read before the Society December 27, 1928*)

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INTRODUCTION

During the last ten years the great batholiths of northeastern Minnesota have been visited many times and studied in considerable detail by parties of the Minnesota Geological Survey. The work has now reached a stage where a summary of the broader relations of these masses can be presented with some confidence. The succession of events disclosed by the study is somewhat more complex than that supposed by earlier workers. The essential facts can perhaps be best indicated by descriptions and sketches of two areas and by brief notes on the others.

It is a pleasure to acknowledge the help received in this work from geologists of the Minnesota Geological Survey and from the Graduate School of the University of Minnesota, which provided funds that made the chemical studies possible.

* Manuscript received by the Secretary of the Society May 22, 1929.
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Basis of the Age Determination

The ages of the batholiths along the boundary have been determined largely by their relations to a series of sediments known on the Vermilion range as the Ogishke conglomerate and the Knife Lake slates, and on Rainy Lake as the Seine conglomerate, arkosite, and schist. This

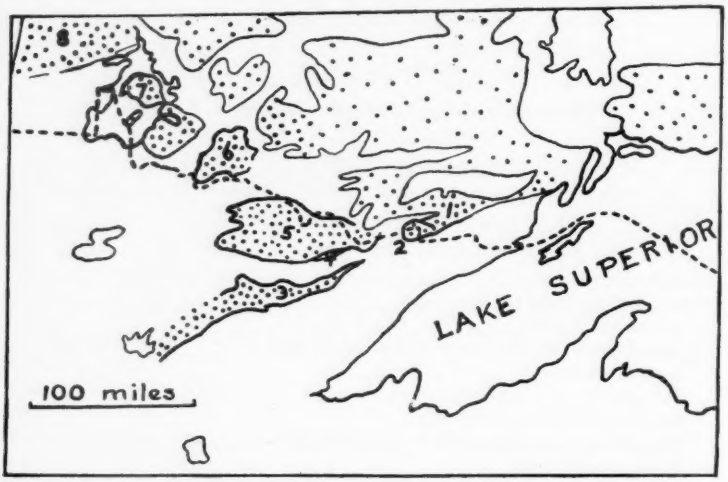

FIGURE 1.—*Sketch of the Boundary of Minnesota and Ontario*

Showing the general location of the main batholiths. More distant masses generalized from the map of North America by Willis. 1. Nothern Light Lake gneiss, Laurentian. 2. Saganaga granite, Laurentian. 3. Giants Range granite, Algoman. 4. Burntside Lake gneiss, Algoman. 5. Vermilion granite, Algoman or later. 6. Rainy Lake masses, Algoman or later. 7 and 8. Lake of the Woods area, Laurentian or later.

series lies between the Archean Keewatin greenstone and the Animikie (Upper Huronian) sediments and may be of Lower and Middle Huronian age, or it may be composed of pre-Huronian or Huronian rocks of a sort not seen at the type locality of the Huronian. Several series of deposits probably lie between the Keewatin greenstone and the Animikie.[1]

Some of the batholiths are earlier and others are later than the Ogishke and Seine sediments. Those that are older than the Ogishke conglomerate are here classed as Laurentian. Those that intrude this conglomerate and unconformably underlie the Animikie are classed as

[1] A. C. Lawson: The Archean geology of Rainy Lake restudied. Canada Geol. Survey Memoir 40, 1913, pp. 80, 81, and 103.

Algoman, a period named by Dr. Lawson [2] and described by him as just preceding the Animikian.

The ages of the batholiths are determined not only by their relation to the sediments, but by their relations to each other; and some indications of their ages may be seen in their petrography.

Saganaga Lake Area

Of the several batholiths on the boundary that have been supposed to be Laurentian, the only one older than the Ogishke conglomerate is the Saganaga granite (figure 2). Its boundaries have recently been

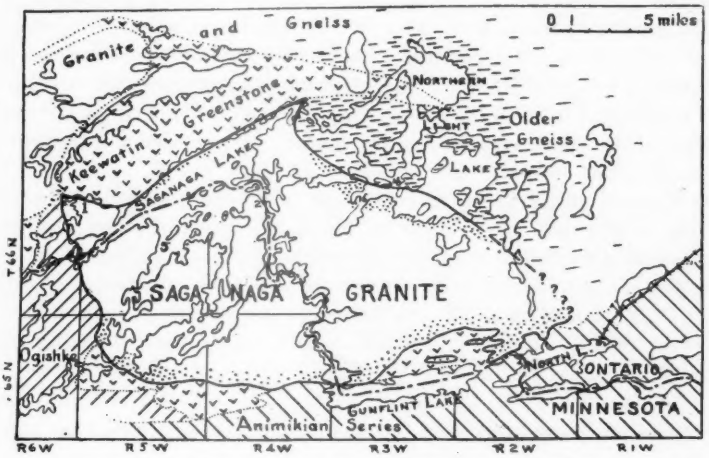

FIGURE 2.—*The Saganaga Batholith and its Surroundings*

The stippled area is a border phase. The older gneiss, northeast of Saganaga Lake, is intruded by the Saganaga granite at the point marked "4" in Northern Light Lake.

closely determined, and the variations in its petrography have been studied microscopically and chemically.[3] About 80 per cent of the rock exposed is a peculiar pink granite containing characteristic quartz "phenocrysts"—so peculiar that its pebbles in the Ogishke conglomerate can be easily identified. For a formation so old it shows remarkably little granulation or gneissic structure and it contains few inclusions, dikes, or other irregularities.

Along the borders of the granite, in a zone that is in places a mile wide, its texture is more even, it contains less quartz, and it is darkened

[2] Op. cit., p. 108.

[3] Frank F. Grout: The Saganaga granite of Minnesota-Ontario. Jour. Geol., vol. 37, 1929, pp. 562-591.

by more hornblende than the central mass. Even the border rocks, however, grade into gneisses at but few places.

Northeast of the Saganaga granite there is an area of granite gneiss. The two rocks, granite and gneiss, have been mapped as extending to Black Bay of Lake Superior,[4] and the prominently gneissic phase extends at least 10 miles from the boundary of the Saganaga granite. The change from granite to gneiss is abrupt and gives a strong impression that the two were formed at two quite different times. The evidence sustaining this impression consists of the following facts: (1) Dikes of the granite, especially of the border phase of the granite, intrude the gneiss (see location 4, figure 2); (2) the gneiss is highly granulated and the granite is remarkably fresh for a formation as old as Laurentian; (3) the gneiss has a regional metamorphic structure trending a little north of east, and the more massive granite transgresses that structure; (4) the granite has a less acid border phase where it is in contact with older rocks, and the gneiss caused a border phase as wide and as distinct as the older Keewatin greenstone.

These several items of evidence have cumulative weight and make it very certain that the gneiss is too old to be considered simply an early phase of the granite intrusive. Nevertheless, as no sediments in this region occupy the interval between the Keewatin greenstone and the Ogishke conglomerate, the two batholiths are assigned to one interval. Both intruded Keewatin greenstone and the younger batholith, the Saganaga granite, contributed pebbles to the Ogishke conglomerate.

It appears that the Laurentian interval was so long that at least two batholiths invaded the rocks in succession in periods which were rather far apart.

In the region here considered there may be some other, though probably small intrusive masses of Laurentian age, for the Ogishke conglomerate includes pebbles of porphyry and granite far west of Saganaga Lake, near Ely.[5]

Burntside Lake Area

The contact rock at Burntside Lake along the Vermilion batholith in northern Saint Louis County, Minnesota, differs notably from that seen elsewhere in the region[6] (see figure 3).

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[4] C. R. Van Hise and C. K. Leith: The geology of the Lake Superior region. U. S. Geol. Survey Mon. 52, plate 1.

[5] A dike in greenstone contains soda and potash in about the same ratio as the Laurentian granite. Minn. Geol. and Nat. Hist. Survey, 21st Ann. Rept., 1893, p. 43.

[6] Frank F. Grout: Geology of northern St. Louis County, Minnesota. Minn. Geol. Survey Bull. 21, 1926, p. 29.

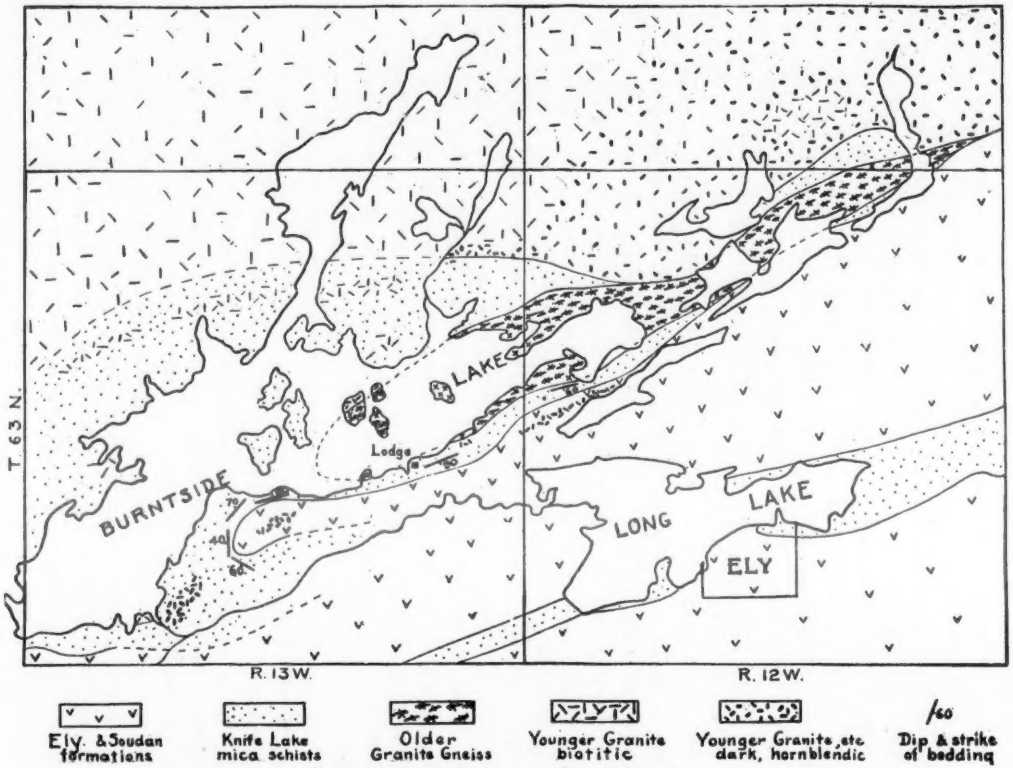

FIGURE 3.—*Formations near Burntside Lake*

Northwest of the "Lodge" the border phase of Vermilion granite intrudes an older gneiss. Both granite and gneiss, however, are younger than the Ogishke-Knife Lake series.

The Vermilion granite is massive over almost the whole of its enormous area, and it shows flow structures only in some of its border phases. So far as known, it is gneissic, as a result of dynamic metamorphism, in only one area, which includes about half a square mile. The granite in this area retains its normal pink color and is not much changed in composition. Most of the batholith as exposed contains abundant inclusions of mica schist, injected lit-par-lit.

Unlike this great, uniform, massive rock, the contact gneiss at Burntside Lake has been granulated by dynamic metamorphism, is uniform throughout the small area exposed, contains few inclusions, and is light greenish gray rather than pink. These features led to the idea that it is a distinct mass, and a careful search made along the contact of the two rocks showed that the border phase of the Vermilion granite intrudes the gneiss.[7] Both rocks, however, intrude the Ogishke-Knife Lake series, and both are cut by later basic dikes, probably of Keweenawan age. As the Animikian was apparently a period of quiet sedimentation in the district, these batholiths were formed either in the Algoman interval (before the Animikian) or in early Keweenawan time. Both have been supposed to be Algoman because the later one, the large Vermilion mass, exhibits a petrographic series similar to that in the nearby Giants Range batholith, which was eroded before the Animikian sediments were formed. This fact, however, is not wholly conclusive evidence of the pre-Animikian age of the Vermilion mass, which resembles in some ways the Killarnean batholiths, supposedly Keweenawan. As the Burntside mass is earlier than the Vermilion mass, it may be safely assigned to the Algoman.

Other Batholiths along the Boundary

The Vermilion batholith, the largest mass on the boundary, is one of the two at Burntside Lake. It has been studied in detail[8] (see figure 1, mass number 5, and Table II).

The Giants Range batholith, studied by Doctor Allison,[9] extends to a point within a few miles of the boundary. It was formed during a sharply defined interval between the deposition of the Knife Lake slates and the Animikian sediments—the Algoman interval (see figure 1).

On Rainy Lake a series of batholiths, best developed on the Canadian side, extends to the boundary. These batholiths were studied by Lawson, who reports that they include granites of both Laurentian and Algo-

[7] Frank F. Grout: Op. cit., plate vi, A.

[8] Frank F. Grout: The Vermilion batholith. Jour. Geol., vol. 33, 1925, pp. 467-487.

[9] I. S. Allison: The Giants Range batholith of Minnesota. Jour. Geol., vol. 33, 1925, pp. 488-508.

man age,[10] both dominantly orthoclase granites. Parsons, who found better exposures, discovered that the granites are Algoman rather than Laurentian.[11] Near the Minnesota-Ontario boundary the best evidence of age cited by Lawson is found on the east side of Review Island, where a dark phase of "Algoman" batholith is said to intrude an older-looking "Laurentian" granite; but unfortunately this locality is permanently flooded by a dam at the outlet of the lake. Farther southwest, at the Minnesota shore of the lake, few exposures furnish conclusive evidence. Where the contact first reaches the mainland the evidence is fairly clear that the so-called "Laurentian" granite of the southern belt intrudes and is younger than the "Algoman" granite of the northern belt. Both intrude the sedimentary Seine series, and they seem to be comparable with the two granites younger than Laurentian at Burntside Lake. In this place, as in that, the evidences that they are Algoman rather than Keweenawan are the petrographic series (see figure 4), which resembles that in the Algoman granite of the Giants Range, and the fact that they are intruded by Keweenawan dikes that have chilled borders.

There are, to be sure, certain granites in the Rainy Lake district that are Laurentian, in the sense that they are older than the Seine conglomerate. Many of the boulders of that conglomerate are granite, but their source is not exposed in clear relation to the associated formations near the boundary.

One rhyolite in the Keewatin complex may indicate the nature of the Laurentian granites of Rainy Lake. Its analysis (number 1 of Table 1) shows that it contains all the chemical features of an igneous rock, although it is now a mica schist not easily distinguished in the field from the schist of the sedimentary Seine series.[12]

Finally, at Lake of the Woods, some large batholiths on the Canadian side reach across the boundary near Northwest Angle. The wall rocks have not been divided by detailed work sufficiently to show whether or not there are Huronian sediments. The freshness of the granites suggests their equivalence with the Rainy Lake and Vermilion batholiths (see analysis 2, Table I). The alkalies in a specimen of the mass at the north tip of Northwest Angle are Na_2O, 3.14 per cent; K_2O, 4.81 per cent.

[10] A. C. Lawson: The geology of Rainy Lake restudied. Canada Geol. Survey Mem. 40, 1913. A. N. Winchell also said the granite at Koochiching Falls, out of Rainy Lake, seems to be Laurentian. Amer. Geol., vol. 20, p. 293.

[11] A. L. Parsons: Mineral developments in northwestern Ontario. Ont. Bur. Mines, 27th Ann. Rept., 1918, p. 178.

[12] Analyses of the sedimentary schists are given by Lawson (op. cit., p. 34) and by Grout in Minn. Geol. Survey Bull. 21, p. 19.

Besides these batholiths there are several smaller stocklike masses near the boundary, which might be significant if they could be correlated

TABLE I.—*Analyses of certain igneous Rocks near the Minnesota-Ontario Boundary*

	Keewatin	Laurentian or later	Algoman or later			
	Rainy Lake	Lake of the Woods	Rainy Lake		Snowbank Lake	Kekequabic Lake
			Hopkins Bay	Rest Island		
	1	2	3	4	5	6
SiO_2	74.71	73.99	68.62	67.47	69.50	66.84
Al_2O_3	11.82	11.93	15.70	15.91	16.86	18.22
Fe_2O_3	2.27	2.11	1.66	2.13	.50	2.27
FeO	3.60	.77	1.77	1.78	.64	.20
MgO	.76	.41	1.28	1.37	1.45	.81
CaO	1.06	.94	3.56	3.93	1.70	3.31
Na_2O	2.81	2.15	5.08	4.48	4.58	5.14
K_2O	2.08	6.03	1.31	2.84	3.94	2.80
H_2O+	.16	1.12	.56	.36	.42	.46
H_2O-	.38	.16	.10	.04	.20	.....
CO_2	.51	none	trace	.....	.....	.....
TiO_2	.31	.89	.26	.30	.53	.....
ZrO_2	.....	.06	.....	.....	.....	.....
Cr_2O_3	.....	none	none	.....	trace	.....
MnO	.....	.02	.07	.....	trace	.....
BaO	.....	trace?	.02	.....	.....	.....
P_2O_5	.....	.04	.10	.....	.....	trace
S	.....	.06	.03	.....	.....	.....
	100.47	100.68	100.12	100.61	100.32	100.05
Specific gravity	2.673	2.612	.....	.....	2.648	.....

1. Schistose rhyolite, south shore of Grassy Island, Rainy Lake. F. F. Grout and George Ward, analysts.

2. Granite of large batholith in Manitoba, south of Winnipeg River, Manitoba, near Ontario-Minnesota boundary. Collected by C. H. Stockwell. George Ward, analyst.

3. Granite gneiss, north side of Hopkins Bay, Rainy Lake. M. F. Connor, analyst. A. C. Lawson, Memoir 40, 1913, p. 93.

4. Granite from island southwest of Rest Island, Rainy Lake. Ira H. Cram, analyst. Thesis, University of Minnesota.

5. The biotite-granite phase of the Snowbank Lake stock. C. W. Sanders, analyst. Jour. Geology, vol. 37, 1929, pp. 135-149.

6. Augite-soda granite, Kekequabic Lake. U. S. Grant, analyst. Minn. Geol. and Nat. Hist. Survey, 21st Ann. Rept., pp. 39-50.

with the larger batholiths. So far as known, however, they have similar relations and are slightly more alkalic in composition (see Table I).

The Succession of Events

The batholithic activity along this boundary seems to have been more complex than that indicated by the simple terminology, Laurentian and Algoman.[13] These two intervals, to be sure, may possibly be the only ones in the region in which there were batholithic intrusions, but each seems to have been long. There was time in each interval for an early batholith to rise and to become cool, and for conditions to change a good deal before the arrival of a later batholith of that interval. The time may have been long enough to have permitted sedimentation elsewhere in the region between the two invasions.

The suggestion that there was batholithic invasion at two periods in each interval is based on differences in the formations themselves. This kind of evidence may not be universally accepted, but its acceptance does not involve a radical departure from current usage. The granites of Finland, for example, are believed to be of three different ages, but they are not separated in time by any surface formations.[14]

Not every geologist who has studied the granites in the Lake Superior region has assumed that the masses of a single interval were intruded as a single episode. Van Hise and Leith refer to the intricacy of the intrusive action and the separation of intrusions by long periods, as well as the long continuance and complexity in a single mass.[15] Lawson himself, the chief advocate of the idea that all the granites can be assigned to one or the other of two strictly limited revolutions, supposes that these revolutions occupied a long time.[16] However, he did not report evidence of two successive batholiths in a single interval in any district, and he did not suggest that between the two batholithic intrusions in some district there may have been time for sedimentation in some adjoining district.

In order to emphasize the complexity of the series of intrusions their sequence may be tabulated as follows:

Keweenawan	Dike intrusions. *Probable batholithic invasion.* Basic extrusions and intrusions. Sedimentation.

[13] A. C. Lawson: Correlation of the pre-Cambrian. Univ. of Calif. Pub., vol. 10, no. 1, 1916, pp. 1-19.

[14] P. Eskola: On the petrology of the Orijarvi region. Bull. Comm. Geol. de Finlande, No. 40, 1914, p. 10.

[15] Van Hise and Leith: Geology of the Lake Superior region. U. S. Geol. Survey Mon. 52, p. 129.

[16] Op. cit., p. 7.

Probable unconformity

Animikian ..... Sedimentation.

Unconformity

Late Algoman batholithic invasion.
Early Algoman batholithic invasion.

Ogishke (Seine series) ..... Sedimentation.

Unconformity

Late Laurentian batholithic invasions.
Early Laurentian batholithic invasions.

Keewatin ..... Flows and sedimentation.

The idea that there were probably five periods of invasion need cause no surprise. In the Appalachian region the sequence of periods of invasion of batholiths was probably long. Keith says:[17] "In my opinion, the process of intrusion began at least as early as Ordovician . . . culminating in the Permian." Cordilleran batholiths were distributed through the Mesozoic and Cenozoic in very complex fashion; probably in at least five and possibly eight successive epochs. The great invasions near the end of Jurassic and the beginning of Cretaceous time may make the earlier and later invasions insignificant by comparison, but they in no way affect the proof that some were complete before the great Jurassic magmas rose, and that others were scattered along later, the quartz monzonite invasions being in full force in the eastern Cordillera as late as Middle Tertiary.[18] Furthermore, the time from Triassic to Miocene is only about 15 per cent of the whole of geologic time, whereas the time from early Keewatin to the end of Keweenawan is three or four times as great.[19] There is, therefore, plenty of time for a dozen epochs of invasion, but in the boundary areas of Minnesota there are probably representatives of five epochs.

Petrographic Comparison of early and late Batholiths

General conditions

Several geologists working in pre-Cambrian granites have attempted to find local, if not general, petrographic and chemical differences between the older and the younger granites. If such differences could be established, they would be useful in determining the ages of masses that

[17] Arthur Keith: Structural symmetry in North America. Bull. Geol. Soc. Amer., vol. 39, 1928, p. 350.
[18] W. Lindgren: In problems of American geology, pp. 250-278.
[19] Pirsson and Schuchert: Textbook of geology, 2d ed., pt. II, 1924, p. 105.

did not show their age by their field relations. The granites of Mozambique are said to show a progressive increase in the ratio of potash to soda through the pre-Cambrian sequence.[20] It is believed also that the Killarnean granites near Lake Huron can be distinguished from older granites by similar chemical criteria.[21] The magma of the Laurentian granites of New York State is said to have been less viscous and to have intruded schists lit-par-lit more intricately than the Algoman magmas.[22] Lawson attempted to find petrographic criteria for two periods of invasion at Rainy Lake.[23] Eskola lists nine petrographic differences between younger and older granites in Finland,[24] though he states that the chemical differences are slight. Sederholm, however, states that a series of four granites of Finland show a progressive increase in the ratio of potash to soda.[25]

In many parts of the Canadian Shield there are granites of two or more kinds and probably of two or more periods, but too little is known of the age of any of them to permit a fair test of the uniformity or limits of variation of the batholiths of any period.[26] It may be desirable, however, to attempt such a test in a tentative way, using the data for those batholiths along the boundary for which the sequence and the age are most definitely known.

The data for the Laurentian rocks are supplied by two batholiths, a gneiss on Northern Light Lake and a granite on Saganaga Lake. For the Algoman there is the Giants Range batholith and the small masses on Burntside Lake and in Rainy Lake. There are, in addition, a number of large batholiths for which the data are less definite; they are probably Algoman, certainly not older, but they may be as young as Keweenawan. These include the Vermilion batholith, several on Rainy Lake and Lake of the Woods, and some stocks, such as those at Snowbank Lake and Kekequabic Lake.

PETROGRAPHIC AND CHEMICAL CRITERIA

Detailed petrographic study has disclosed some features in certain ones of these batholiths which are not seen in others, but some comments must accompany each statement, as to its probable applicability as a criterion for distinguishing masses of different age.

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[20] A. Holmes: Theory of magmatic cycles. Geol. Mag., vol. 63, 1926, p. 317.
[21] W. H. Collins: Personal communication.
[22] H. L. Alling: Origin of graphite. Econ. Geol., vol. 16, 1921, p. 337.
[23] A. C. Lawson: Correlation of the pre-Cambrian. Univ. of Calif. Pub., vol. 10, no. 1, 1916, pp. 15-16.
[24] P. Eskola: Op. cit., pp. 28-32.
[25] A. Holmes: Op. cit., p. 317.
[26] J. F. Wright: Personal communication, October, 1928.

The inclusions in Laurentian granites are limited to the greenstone, a hornblende schist. Those in the later granites are greenstone at a number of places, but much more characteristically mica schist derived from the sediments. Some large areas, however, of both older and younger rocks are almost free from inclusions, and, of course, this criterion can be used only where inclusions are abundant.

Microcline, as contrasted with orthoclase, was found mostly in the early Laurentian gneiss on Northern Light Lake; in the Vermilion batholith, which is of Algoman or Killarnean age, and in the Giants Range Algoman rocks; but it is found also in Laurentian rocks. In several of these rocks there is a suggestion that it has been formed chiefly by alteration, but in the Vermilion mass, where it is most abundant, much of it seems to be primary. It is more abundant and less a result of alteration in the Vermilion and associated masses than in older rocks, but its mere presence is not a sign of age.

The late Laurentian Saganaga batholith contains, near its center, large aggregates of quartz, suggesting phenocrysts, which are not seen in the earlier gneiss nor in any later masses in the region; but even the borders of the same mass lack such "phenocrysts," so that they may not be a very characteristic feature of the rocks of one epoch.

Graphic intergrowths were noted, mostly in the Vermilion granite and its pegmatites and in the Giants Range Algoman granite. They are lacking in the altered rocks of both Laurentian and Algoman age; but the Saganaga Laurentian mass is very fresh, and since graphic intergrowths are lacking here also, they probably never were formed. Their absence in fresh granite may be a criterion of Laurentian age, as has been suggested for the Finland granites.

Fluorite was seen only in a small area of late Laurentian Saganaga granite. It is not at all characteristic of the mass as a whole and its presence in masses of other ages would not be surprising. In Finland fluorite is characteristic of the younger granites rather than the older,[27] a fact which contravenes the suggestion that it may be a criterion of Laurentian age.

Notably alkaline rocks have not been found in any of the larger batholiths, but some stocks that seem related to the Algoman batholiths are alkalic;[28] but, since few Laurentian masses are available, further studies of the rocks in Laurentian areas may show that alkalic rocks are as abundant in them as in Algoman or later areas.

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[27] P. Eskola: Op. cit., pp. 29-31.

[28] Frank F. Grout: The Vermilion batholith. Jour. Geol., vol. 33, 1925, pp. 480-482.

FEATURES THAT ARE NOT DISTINCTIVE

Many other detailed petrographic features were carefully sought, but none were found to be characteristic.

The degree of metamorphism is not a satisfactory criterion of age. The earlier of two granites in a district is likely to be the more gneissic; but the earlier at Burntside Lake is Algoman, and the latest granite found near Saganaga Lake is Laurentian. Any suggestion that the Laurentian shows greater metamorphism than the Algoman is based on averages rather than on details, and the averages differ less than two phases of the same batholith. No doubt some Laurentian rock was altered by Algoman intrusives, and the reverse can not occur. In spite of the average, however, the rocks in some large Laurentian areas are massive and those in some Algoman areas are gneissic. There is no criterion here.

The fact that the gneisses look more bleached and grayer than the fresh pink granite is probably related to the degree of metamorphism, so that color is no safer as a criterion than metamorphism.

Trachitoid texture, flow structure, and the like are about equally prominent in masses of different ages, mostly in border zones and in the smaller masses.

The contact effects in the Keewatin greenstone are similar in the batholiths of the two ages. Both inject schists lit-par-lit in some places, but not in all. The most characteristic injection gneisses are the oldest Laurentian and those of the Vermilion batholith, which is probably the youngest of the five.

Myrmekite intergrowths of quartz and acid plagioclase are found in the Saganaga and Vermilion batholiths and are probably absent from the gneisses only because of greater metamorphism.

Perthitic intergrowths also range from early to late masses, but are absent from the more altered gneissic masses for the same reason.

In all the batholiths the inclusions in quartz are both liquid and gas. Secondary crystal inclusions are found in the more gneissic rocks, but they show little relation to age.

The sequence of crystallization is not notably different in the several masses.

The composition of the magma and the nature of the differentiated series of rocks are, of course, not identical in all the batholiths, but no feature of the rocks seems to be logically related to age except, possibly, the ratio of potash to soda. The series of rocks that covers the greatest range in composition is that in the Vermilion batholith. If the analyses are plotted according to content of alkali and silica, the series of the

Algoman batholith of the Giants Range and the Laurentian batholith of Saganaga Lake approach very closely the same curve (see figure 4). There is no criterion of age in this feature.

In contrast to the petrographic series in these batholiths of several ages, great petrographic uniformity is shown by two batholiths—that at Burntside Lake and that at Northern Lake—but one of these is Lauren-

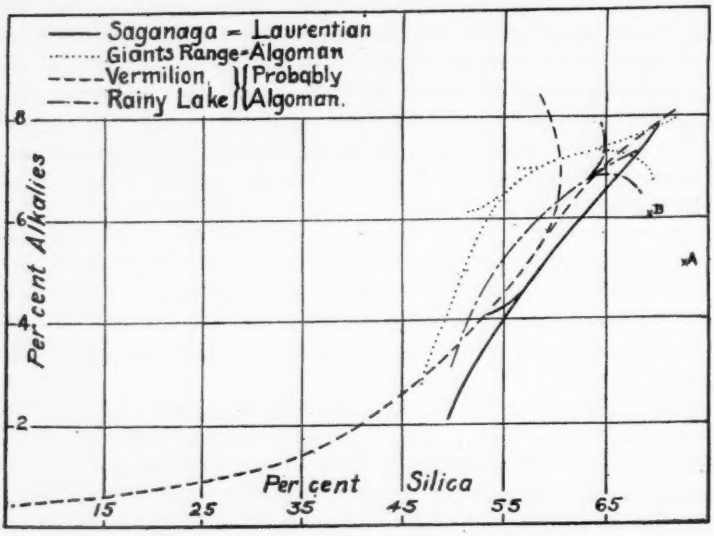

FIGURE 4.—*Curves of Variation in Composition of Some Batholiths*

Location of these batholiths is along the Minnesota-Ontario boundary.

The Laurentian masses (solid line) can hardly be distinguished from those of later age. There are more differences in the masses of one period than between those of two different periods.

The cross at A indicates the composition of an early Laurentian granite, not much differentiated, but very different from the series shown by the solid line. The cross at B shows an early Algoman granite.

Data for the Giants Range are taken from Allison, for Rainy Lake from Lawson and from Cram, for others, by the writer; all in papers already cited.

tian and the other is Algoman, so that petrographic uniformity is no indication of age.

The ratio of soda to potash differs in the main masses and in the averages of different batholiths. This difference is of course shown by the minerals, but is not a good field criterion, because, while it is common for the potash feldspar to be pink and the albite white and striated, there are considerable areas of red albite that show no megascopic striations. The data for minerals and for alkalies are summarized in Table

II. Data for Manitoba and for the Killarnean granites are averages from Table III; data for miscellaneous Minnesota granites are given in Table I; data for the Algoman Giants Range were given by Allison;[29] data for the Vermilion and other Algoman[30] and for the Laurentian[31] are taken from the writer's earlier papers.

TABLE II.—*Summary of Alkali Ratios and Age*

		Na_2O	K_2O
Manitoba granites	3 Older	4.22	1.78
	3 Younger	3.68	2.99
Minnesota granites of known age	2 Laurentian	4.54	1.83
	2 Algoman	4.95	1.61
Minnesota stocks and batholiths	5 probably Algoman	3.89	3.75
Minnesota, Vermilion batholith	1 mass, 6 analyses, Algoman or later	3.85	4.70
Ontario, Killarney	Several masses, seven analyses, Killarnean	3.35	4.68
Series of phases, Vermilion batholith (Algoman or Killarnean)		1.39	0.43
		4.03	1.36
		3.09	2.01
		4.56	3.54
		3.58	4.63
Series of phases, Giants Range batholith (Algoman)		1.91	0.89
		2.38	1.71
		4.69	2.34
		4.00	3.75
		3.03	4.79
Series of phases, Saganaga batholith (Laurentian)		6.47	1.26
		4.49	0.94
		4.78	1.72
		3.78	2.39
		4.78	3.06

It is especially important to note that there is more variation in a single batholith in phases that occur in considerable volume than there is between batholiths of one period and those of another. Any criteria based on the ratio of feldspars or of alkalies should be applied with the greatest caution.

The table of alkali ratios, moreover, brings out strikingly the fact that the Vermilion granite resembles the Killarney granites north of Lake

[29] Allison: Op. cit., p. 505. Analyses I and J, by R. J. Leonard, are erroneous in the determinations of alkalies. The data should be as follows:

	I	J
Na_2O	3.03	4.00
K_2O	4.79	3.75

These are both from late phases of the Giants Range mass.

[30] Minn. Geol. Survey Bull. 21, pp. 29, 35 and 48.

[31] The Saganaga granite of Minnesota-Ontario. Jour. Geol., vol. 37, 1929, pp. 562-591.

Huron, rather than any other group. As the age of the Vermilion granite is not determined by its contact with later sediments, it may be of the same age as the Killarnean, which, according to Collins, is late pre-Cambrian, possibly Keweenawan.[32]

TABLE II.—*Approximate Modes of the main granite Phases of Batholiths near the Minnesota-Ontario Boundary*

	Quartz	Ortho-clase	Micro-cline	Plagio-clase	Bio-tite	Horn-blende
Northern Light Lake (early Laurentian)	30	15	1	48	6	.....
Saganaga Lake (late Laurentian)	30	25	+	35	.....	10
Burntside Lake (early Algoman)	25	30	2	40	2	1
Giants Range (Algoman)	17	26	7	35	5	10
Vermilion (Algoman or later)	25	30	20	20	2	.....

DATA FROM OTHER PARTS OF THE CANADIAN SHIELD

During the last few years several geologists working in Canada have collected excellent material from batholiths in the Canadian Shield. The data have been accumulated slowly, but some of the analyses may be suggestive. Thanks are due for a large part of the material to Dr. W. H. Collins, Director of the Geological Survey of Canada, and the men in his field parties.

SUMMARY OF CRITERIA

Very few of the several petrographic criteria suggested for the correlation of the granites in this or any other region have survived a detailed study of the batholiths northwest of Lake Superior. Even in the few batholiths whose ages have been determined, the petrographic variation is so great that it is hard to find any feature not represented in masses of very different ages. Two sorts of criteria may be worthy of further study—the inclusions and certain minerals.

Few inclusions of mica schist are found in Laurentian granites, but many are found in some of the later granites.

The mineral features that are apparently limited to Laurentian granite in this area are the presence of fluorite and of large "phenocrysts" of quartz; but these are lacking even in much of the Laurentian rock. The feature of the Algoman that is not seen in the Laurentian is micropeg-

[32] W. H. Collins: North shore of Lake Huron. Canada Geol. Survey Memoir 143, 1925, pp. 93-94.

TABLE III.—*Analyses of certain Batholiths of the Canadian Shield*

	Island Lake		Oxford Lake		Winnipeg		North of Lake Huron						
	Old	Young	Old?	Young?	Old?	Young?	Killarnean; probably much younger						
	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	72.73	68.59	68.06	71.24	70.52	68.26	71.63	72.01	70.48	68.85	72.14	71.36	.....
Al_2O_3	14.86	18.63	15.94	16.51	16.25	17.35	16.00	17.17	15.82	14.53	13.32	14.88	.....
Fe_2O_3	trace	trace	1.01	.15	.56	.43	.07	.28	1.55	1.29	1.91	.90	1.47
FeO	2.79	2.43	2.40	1.44	1.64	1.99	1.08	1.11	1.07	2.64	2.31	1.22	
MgO	1.52	1.09	1.46	1.32	.80	.65	.40	.37	.09	1.04	.24	.56	
CaO	2.33	3.24	4.61	.33	1.62	2.98	1.38	.94	.30	.99	1.11	1.77	
Na_2O	4.73	3.25	4.18	3.24	3.76	4.54	3.06	2.64	3.50	3.02	3.41	3.23	2.58
K_2O	.80	1.88	1.69	3.85	2.85	3.25	4.76	4.02	5.70	5.69	4.41	4.52	3.66
H_2O+	.46	.48	.25	.10	.62	.30	.56	.52	.60	.40	.32	.81	.....
H_2O-	.02	.12	.20	.92	.30	.58	.22	.22	none	.10	.04	none	.....
CO_2	.30	.20	.21	trace	trace	trace	.97	1.02	.....	.....	.....	none	.....
TiO_2	trace	.18	.36	.28	.17	.13	.13	.13	.35	.58	.35	.18	.....
ZrO_2	.....	.06	.01	.02	.14	.06	.....	.07	.13	.04	.....	.....	.....
P_2O_5	.....	.08	.19	.16	.29	.20	.....	.15	.09	.21	.06	.30	.....
S	.12	.....	.02	.07	.09	.08	.....	.03	.02	.01	.....	none	.....
Cr_2O_3	.....	.....	trace	trace	trace	trace	.....	none	.02	trace	.....	.....	.....
MnO	.....	.....	.08	.03	.05	.05	.....	.01	.04	.13	.11	.....	.....
BaO	.....	.....	.02	none	trace	.01	.....	trace	.10	.13	.....	none	.....
Rare earths	.....	.....	.....	.....	.....	.....	.....	.....	.36	.02	.....	.....	.....
	100.66	100.23	100.69	99.66	99.66	100.86	100.26	100.69	100.22	99.67	99.73	99.73	.....

1. Granite of boulder in conglomerate, Island Lake, Manitoba. Collected by J. F. Wright. F. F. Grout and G. W. Ward, analysts.
2. Granite intruding number 1, Island Lake. Same source and analysts.
3. Older gray gneiss, south of Oxford Lake, Manitoba. Collected by J. F. Wright. F. F. Grout, analyst.
4. Younger pink granite, north of Oxford Lake. Collected by J. F. Wright. George Ward, analyst.
5. Older? gray gneiss east of Winnipeg. Collected by J. S. De Lury. George Ward, analyst.
6. Probably younger pink granite, deep drill core near Winnipeg. George Ward, analyst.

7 to 13, inclusive. From the Killarney region; supposedly younger than Algoman.

7. Pale granite, Hyman Township,
8. Red granite, Bigelow Township, Sudbury District. Collected by C. Tolman. George Ward, analyst.
9. Typical fine granite for a mile along the Canadian Northern Railroad, east of Ess Creek station. Collected by Ellsworth. F. Grout, analyst.
10. Allanite gneiss, Collins Inlet. Collected by H. V. Ellsworth. F. F. Grout, analyst.
11. Granite, west of Killarney. Collected by H. V. Ellsworth. F. F. Grout, analyst.
12. Gneiss, north side of George Island, Killarney. R. J. C. Fabry, analyst. Furnished by Canadian Geological Survey.
13. Granite, Serpent River. Collected by H. V. Ellsworth. F. F. Grout, analyst.

matite. Alkalic pyroxene and abundant primary microcline may be added to this lone item, but they occur chiefly in masses of less certain age.

The last noteworthy suggestion as to criteria is the ratio of potash to soda. The Laurentian and Algoman, where definitely determined, can not be so distinguished, but the ratio of potash to soda in certain late pre-Cambrian batholiths is greater than that in either the known Laurentian or the known Algoman batholiths. The sequence of pre-Cambrian batholiths, then, shows no regular progression in this respect northwest of Lake Superior; but after the studies have been carried further it may be found that the rock of some particular period is characterized by potash.

No other feature seems worth considering. Taken as a whole, there is more variation in a single batholith than between the main mass of Laurentian and the main mass of Algoman. But this short list of possible criteria is based on very few masses of determined age. Only one fresh Laurentian granite in the region is available for the comparison, and it is very likely that some other Laurentian mass near by may show features that suggest later age and thus ruin the few criteria that now seem available.

Status of the Problem in Minnesota

The contact relations of four granites along the Minnesota-Ontario boundary show that they invaded the region in succession at four different times. The contact relations of several other batholiths do not show whether they should be correlated with these four. At least one very large mass, the Vermilion batholith, is chemically somewhat different from any of those whose age has been determined, resembling the Killarnean granite north of Lake Huron, which is presumably younger than any of the four mentioned.

The Vermilion batholith may be Algoman, but if so the rocks of Algoman batholiths are so variable that their ages can not be determined by petrographic criteria.

On the other hand, if the Vermilion batholith is later than Algoman, say Killarnean, then along the boundary of Minnesota and Ontario we have representatives of five successive batholithic invasions in at least three long intervals. As the intrusives are not in contact with Animikian or Keweenawan surface formations, it is not likely that we can determine their ages by further work in Minnesota.

The petrographic criteria for estimating the age of the granites in this region are weak. Certain features, such as inclusions of mica schist, much primary microcline and micropegmatite, alkaline rocks, and a high ratio of potash to soda, suggest that the rocks are younger than Laurentian. Petrographic criteria, however, should be used with great caution. There is much more petrographic variation inside of a single batholith than between batholiths of different periods.

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